NASA CR-160764

INCREASED CAPABILITY GAS GENERATOR FOR SPACE SHUTTLE APU

DEVELOPMENT/HOT RESTART TEST REPORT

80-R-695

Submitted To:
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058

Under Contract No. NAS 9-16002

July 7, 1980

ROCKET RESEARCH COMPANY

A DIVISION OF ROCKCOR

Redmond, Washington

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Prepared by:

Rocket Research Company
A Division of ROCKCOR, Inc.
York Center
Redmond, Washington 98052

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1.0 INTRODUCTION

This report will define, discuss, and analyze the Development/Hot Restart and Acceptance Testing performed under the NAS9-16002 Contract.

The contracted work included the fabrication of two Development Space Shuttle APU Gas Generators of an improved design.

The intent of the work was to provide a replacement for the GGSS designed in 1974 and modified through the years in an attmept to keep up with the increased performance demands and changes in mission requirements.

In 1977, such a task was initially undertaken but, as a result of fiscal constraints, was put on "hold" in February, 1978. The gas generators delivered under this program are descendants of the design developed under that program (with the significant changes described below). The basic design goals have not changed significantly since February, 1978. In the meantime, however, the incorporation of active cooling in the GGSS, and experience therewith, has shown that fixes to the existing Minor Modification design will in no way address all the long-term gas generator needs and goals. Active cooling, while providing hot restart capability, is limited by cooling time. It also requires complex valving, adds considerable weight to the APU systems, and fails to provide extended life capability.

The primary design goals were to provide an Increased Capability Gas Generator (ICGG) which:

1. Is capable of unlimited hot restart, without the need for an active cooling system.

2. Has greater life than the Minor Modification or Actively Cooled Gas Generators. A structural life of 150 hours with a bed life of 50 hours was the basis for design.

3. Maintain an exposed surface temperature of ≤ 350°F.

1.1 DESCRIPTION OF TEST ITEM

The test items were Improved Capability Gas Generators as defined in RRC SK-6628, Figures 1 and 2. An isometric view is presented in Figure 3. This is a radial flow, monopropellant, hydrazine reactor. This design will interface with the Space Shuttle APU in the same way as the Minor Modification Gas Generator. The only differences are in the electrical connections which are hard-mounted on the ICGG, the fact that some insulation on the ICGG must be installed after the ICGG is in the APU, and the heat shield is considerably changed.

The ICGG incorporates several hardware modifications to the Minor Modification/Active Cooling design as described below:

(a) The hexagonal injector with four flat Rigimesh panels (Figure 4) is replaced with a cylindrical configuration (SK 6627, Figure 5), using three curved Rigimesh panels. The panels are EB-welded into place on both of these configurations. This is appreciably different that the original "New Design" Gas Generator which, while incorporating a cylindrical injector, utilized Poroloy diffuser element which slipped over the injector body.

(b) The catalyst bed has been lengthened axially to lower the bed loading (for $\dot{w}$ = .265 lbm/sec) to a level approximately equal to that of the original OV-101 configuration (at $\dot{w}$ = .217).

(c) The injector incorporates the branch tube design with three

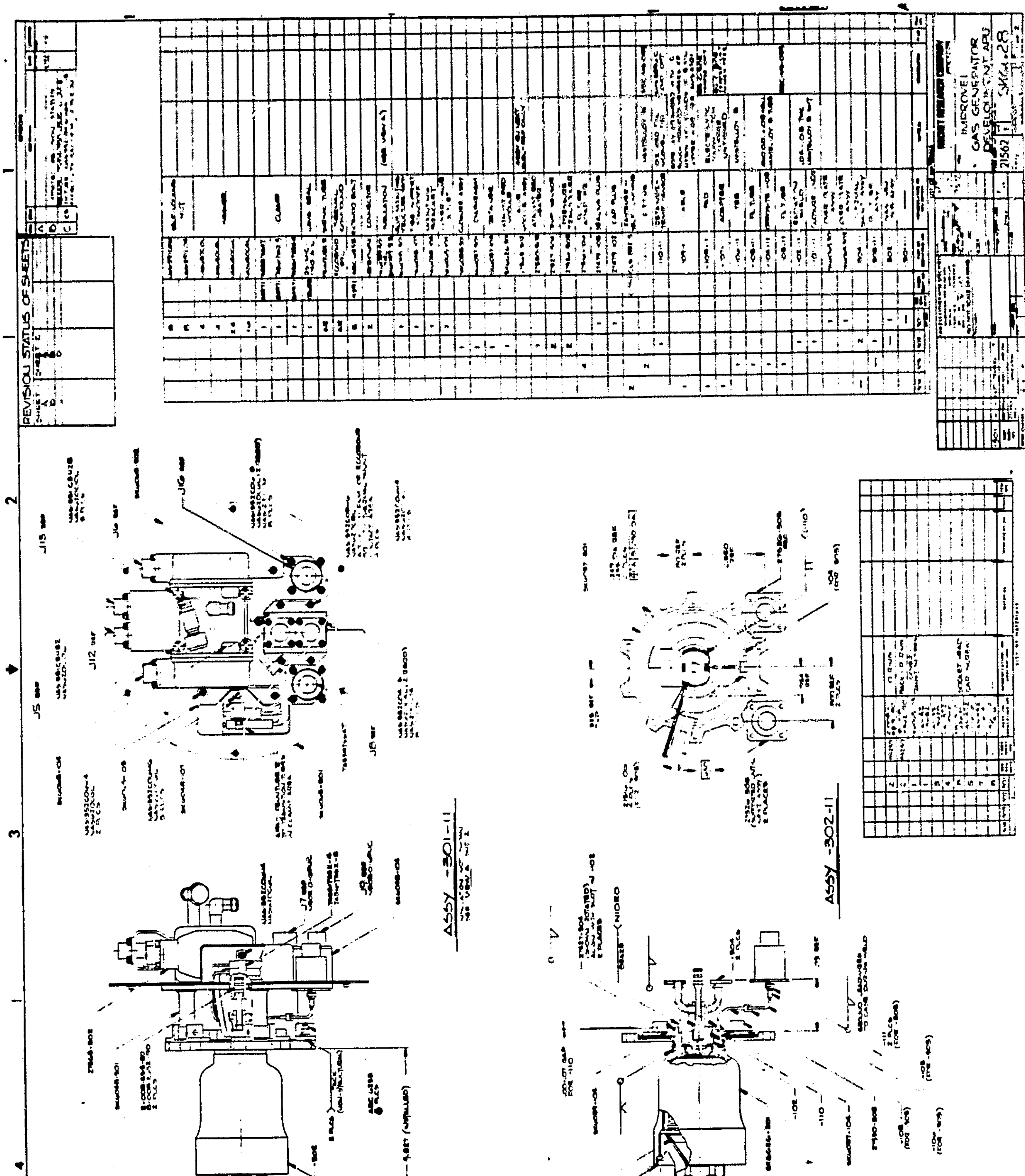
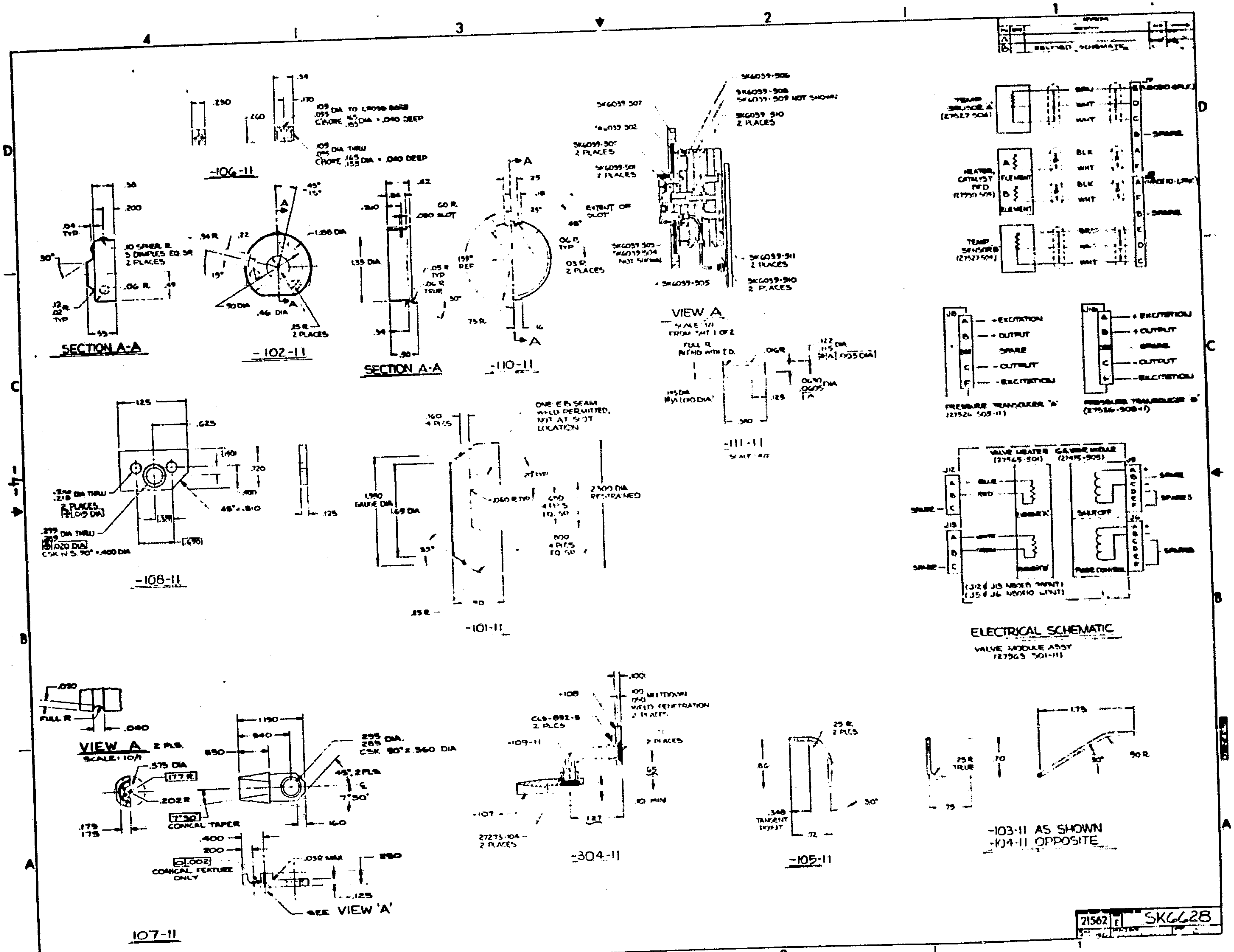

REVISION STATUS OF SHEETS
ASSY -301-11
ASSY -302-11
IMPROVED
GAS GENERATOR
21562
J15
J16
J12
J5
J8

FIGURE 1



SECTION A-A
-106-11
-102-11
-110-11
VIEW A
-111-11
-108-11
-101-11
ELECTRICAL SCHEMATIC
VALVE MODULE ASSY
(27565 501-11)
PRESSURE TRANSDUCER 'A'
PRESSURE TRANSDUCER 'B'
VALVE HEATER
SHUTOFF
SPARE
VIEW A
SEE VIEW 'A'
CONICAL TAPER
CONICAL FEATURE ONLY
107-11
-304-11
-105-11
-103-11 AS SHOWN
-104-11 OPPOSITE
21562
SK6628

FIGURE 2

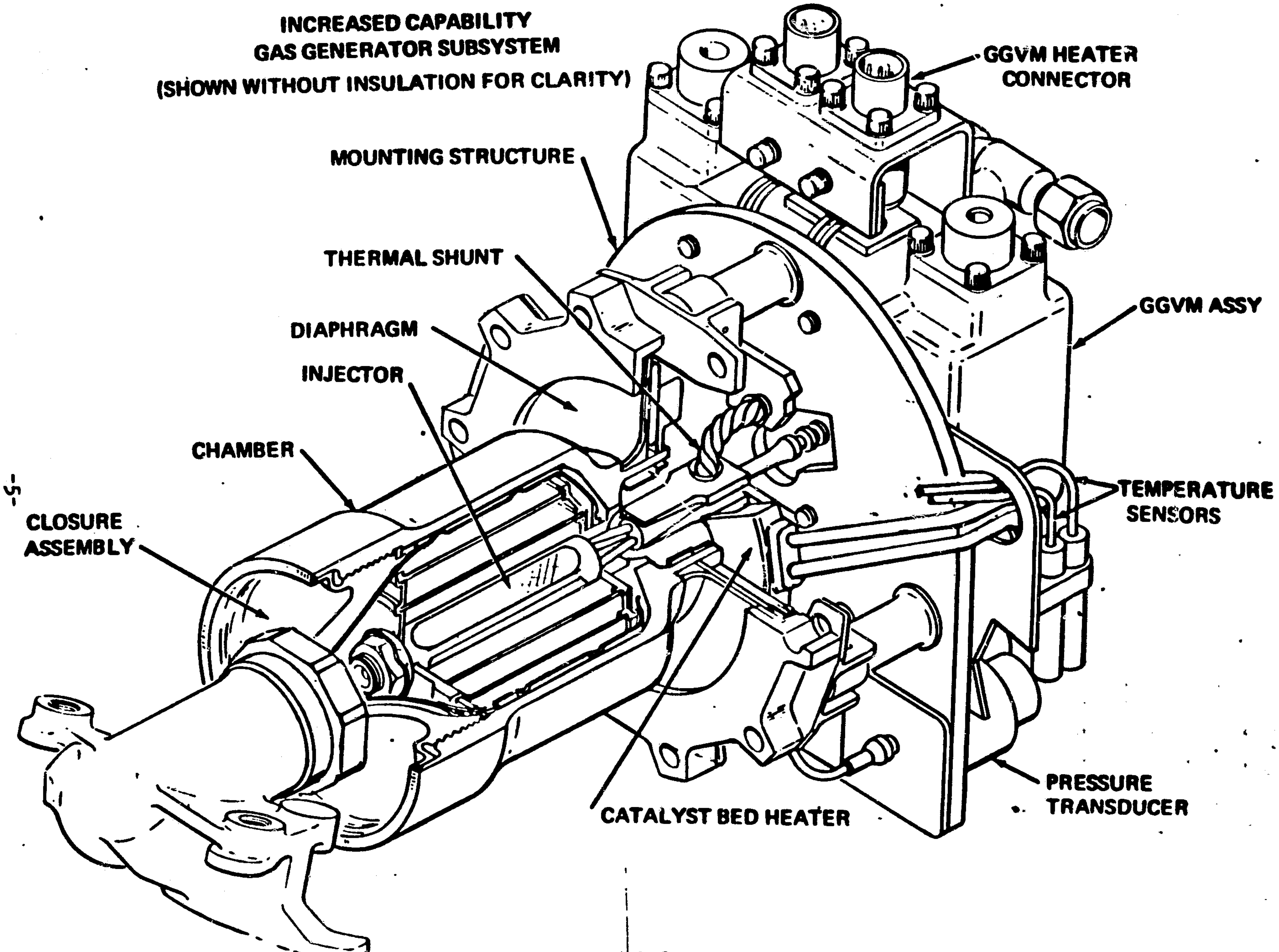
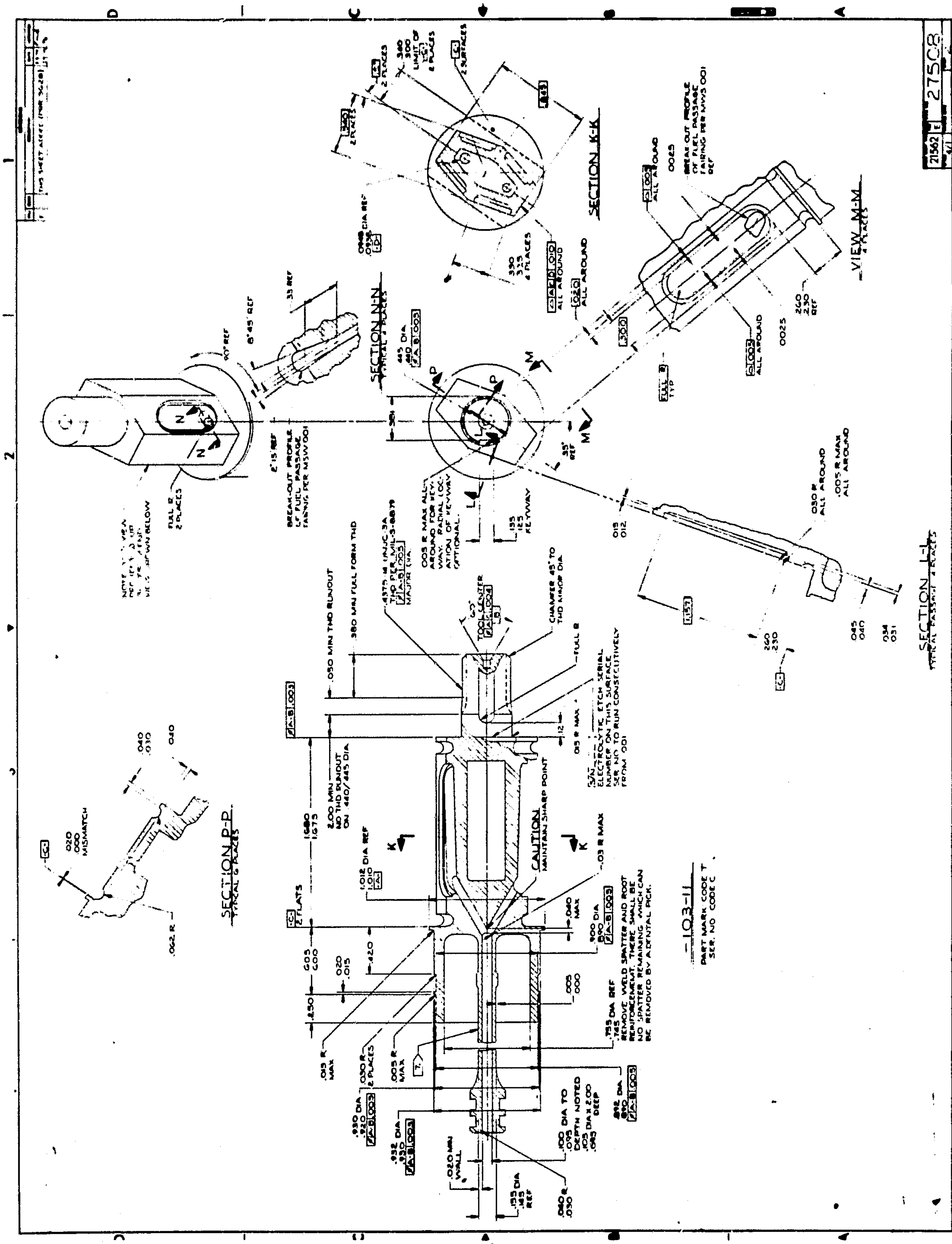
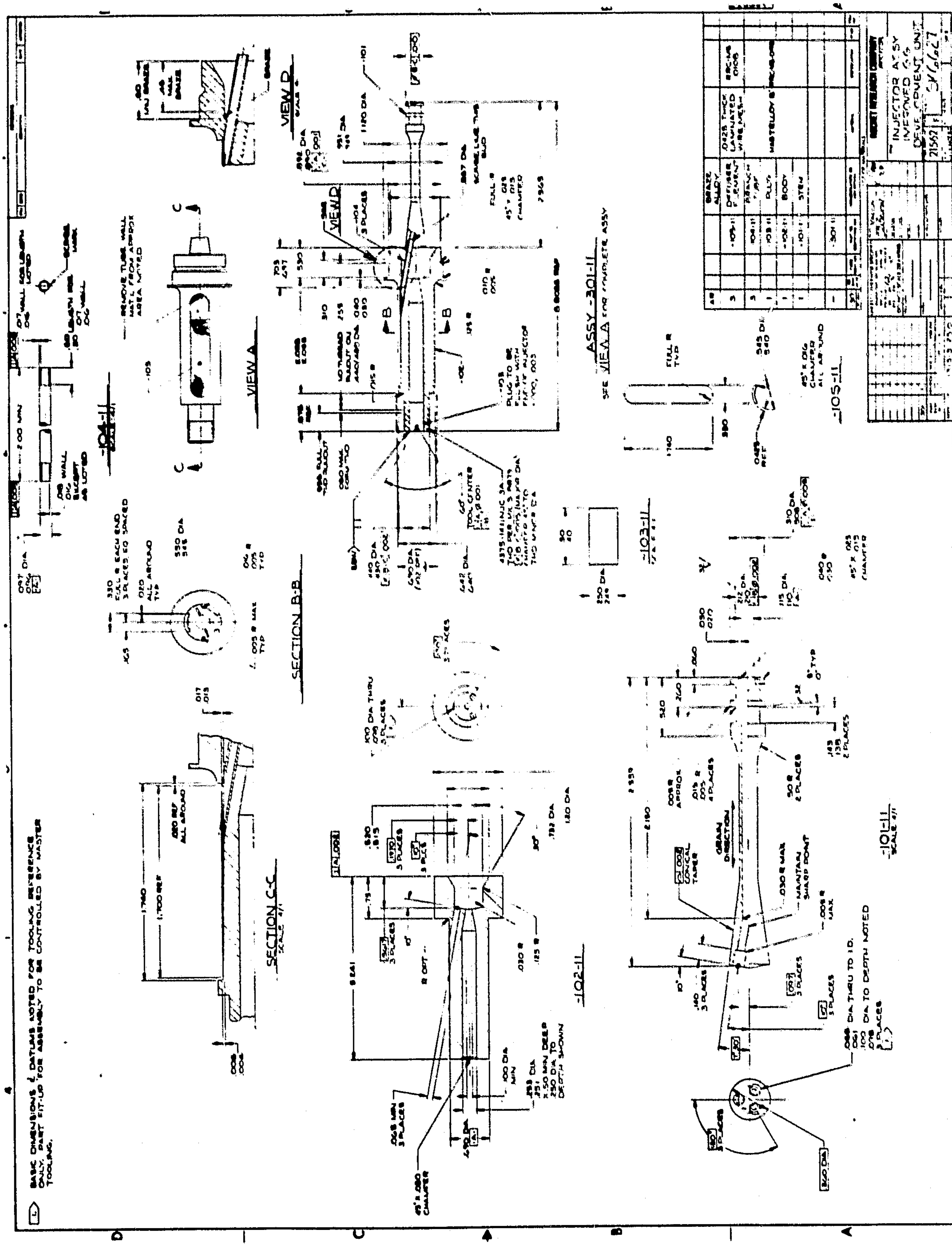

INCREASED CAPABILITY
GAS GENERATOR SUBSYSTEM
(SHOWN WITHOUT INSULATION FOR CLARITY)
GGVM HEATER CONNECTOR
MOUNTING STRUCTURE
THERMAL SHUNT
GGVM ASSY
DIAPHRAGM
INJECTOR
CHAMBER
TEMPERATURE SENSORS
CLOSURE ASSEMBLY
CATALYST BED HEATER
PRESSURE TRANSDUCER

FIGURE 3


SECTION K-K
VIEW M-M
SECTION N-N
SECTION L-L
SECTION P-P
CAUTION
MAINTAIN SHARP POINT
-103-11
PART MARK CODE T
SER. NO. CODE C
ELECTROLYTIC ETCH SERIAL NUMBER ON THIS SURFACE SER. NO. TO RUN CONSECUTIVELY FROM 001
REMOVE WELD SPATTER AND ROOT REINFORCEMENT. THERE SHALL BE NO SPATTER REMAINING WHICH CAN BE REMOVED BY A DENTAL PICK.
21562
275C8
FIGURE 4



VIEW A
VIEW D
SECTION B-B
SECTION C-C
ASSY -301-11
-101-11
-102-11
-103-11
-104-11
-105-11
BASIC DIMENSIONS & DATUMS NOTED FOR TOOLING REFERENCE ONLY. PART FIT-UP FOR ASSEMBLY TO BE CONTROLLED BY MASTER TOOLING.

FIGURE 5

1.1 DESCRIPTION OF TEST ITEM (continued)

brazed-in branch tubes which was utilized on the "New Design". (Ref. SK-6627, Figure 5).

(d) The ICGG uses two temperature sensors and two pressure transducers to provide redundancy in critical instrumentation.

(e) The thermal shunt is brazed to the injector stem.

The components utilized in these tests included:

(a)	Gas Generator	:	RRC	P/N SK-6628 S/N D204, D204A and D205
(b)	GGVM	:	RRC	P/N 27563-301

1.2 GOALS

The goals of these tests were to:

1. Demonstrate the ability of the ICGG configuration to safely hot-restart, (for a bed in early life) at inlet pressures varying from 80 to 400 psi and soakback times of 5 seconds to 30 minutes. These tests were performed without bubbles in the fuel system, as this was not witnin the scope of the contract nor achievable without extensive design and fabrication of special test hardware.
2. Determine the effect of both Mission Duty Cycle and Hot Restart type firings on the bed, within the first few hours of bed life. The Pc roughness, tailoff times, and pulse shapes provide a basis for comparing catalyst bed condition.

1.2 GOALS (continued)

3. By Acceptance Testing, evaluate the performance of the Increased Capability Design Gas Generator (ICGG). Compare standard performance criteria of the ICGG with the Minor Modification / Actively-Cooled Gas Generator configuration.

1.3 SCOPE OF TESTING (Figures 6 and 7).

1.3.1 Acceptance Tests

Acceptance Tests were performed per TP-0467. The test procedure was essentially identical to TP-0359 used on the Minor Modification Gas Generator Production Testing. The detailed procedures were described phase-by-phase in Appendices "A" through "E".

1.3.1.1 External Leakage, Proof Pressure, Envelope Verification - Appendix "A"

The Gas Generators were subjected to a proof pressure of 2250 psig for a period of five (5) minutes using GN_2 pressurant with no visible damage or deformation.

An external leak check was performed by pressurizing the Gas Generator with Helium to 1500 psig. The leakage, measured with a Mass Spectrometer, did not exceed 1×10^{-4} cc/sec.

An interface/envelope check was performed to assure dimensional acceptability of the gas generator.

1.3.1.2 Test Firing - Appendix "B"

The gas generators were mounted in a sea-level test facility simulat-

FIGURE 6

S/N D204 / D204A TEST SEQUENCE SUMMARY

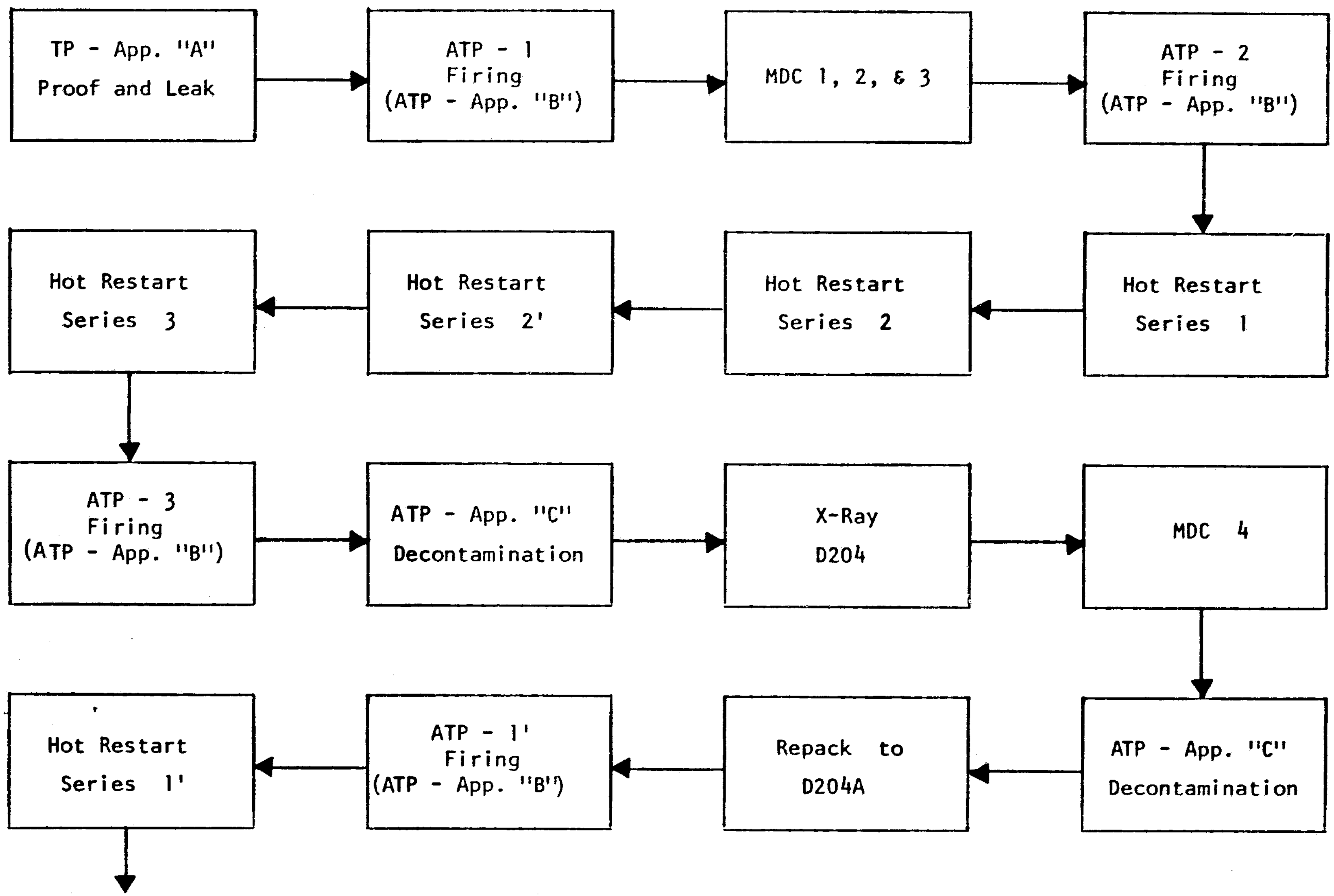
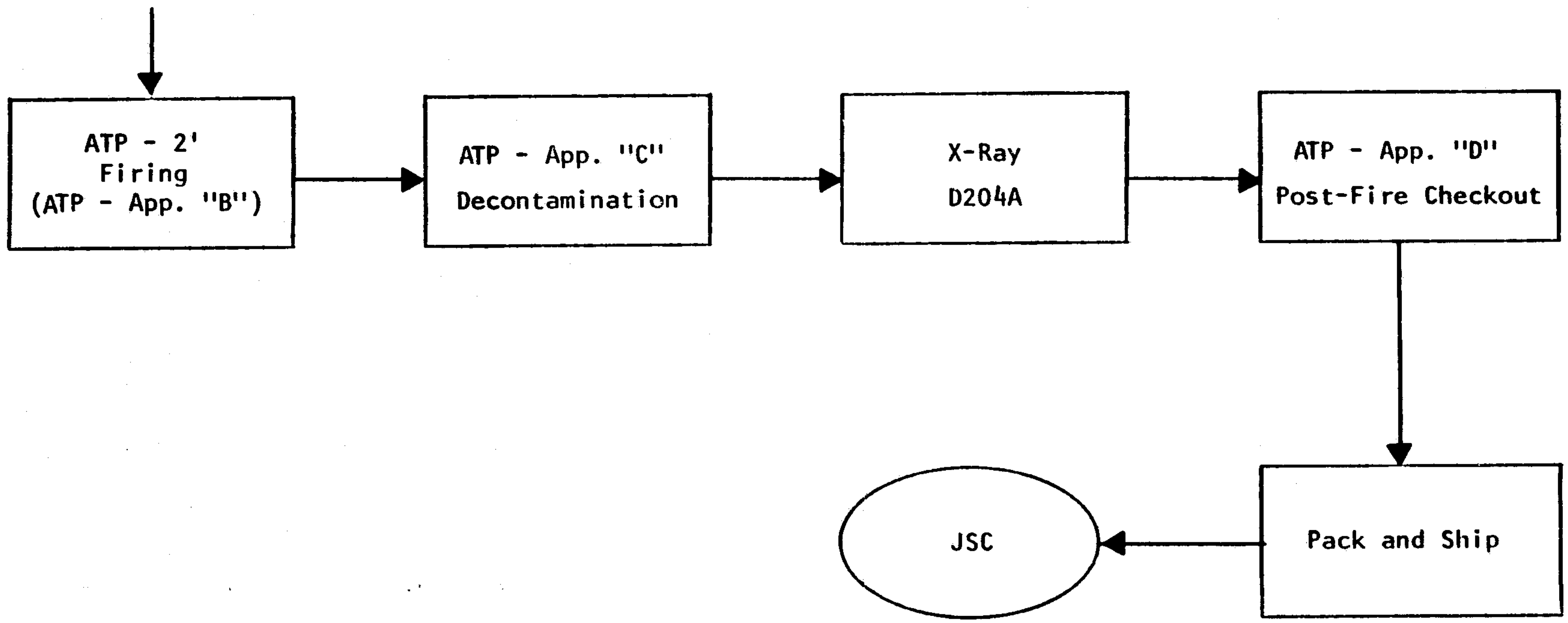


FIGURE 6 (continued)



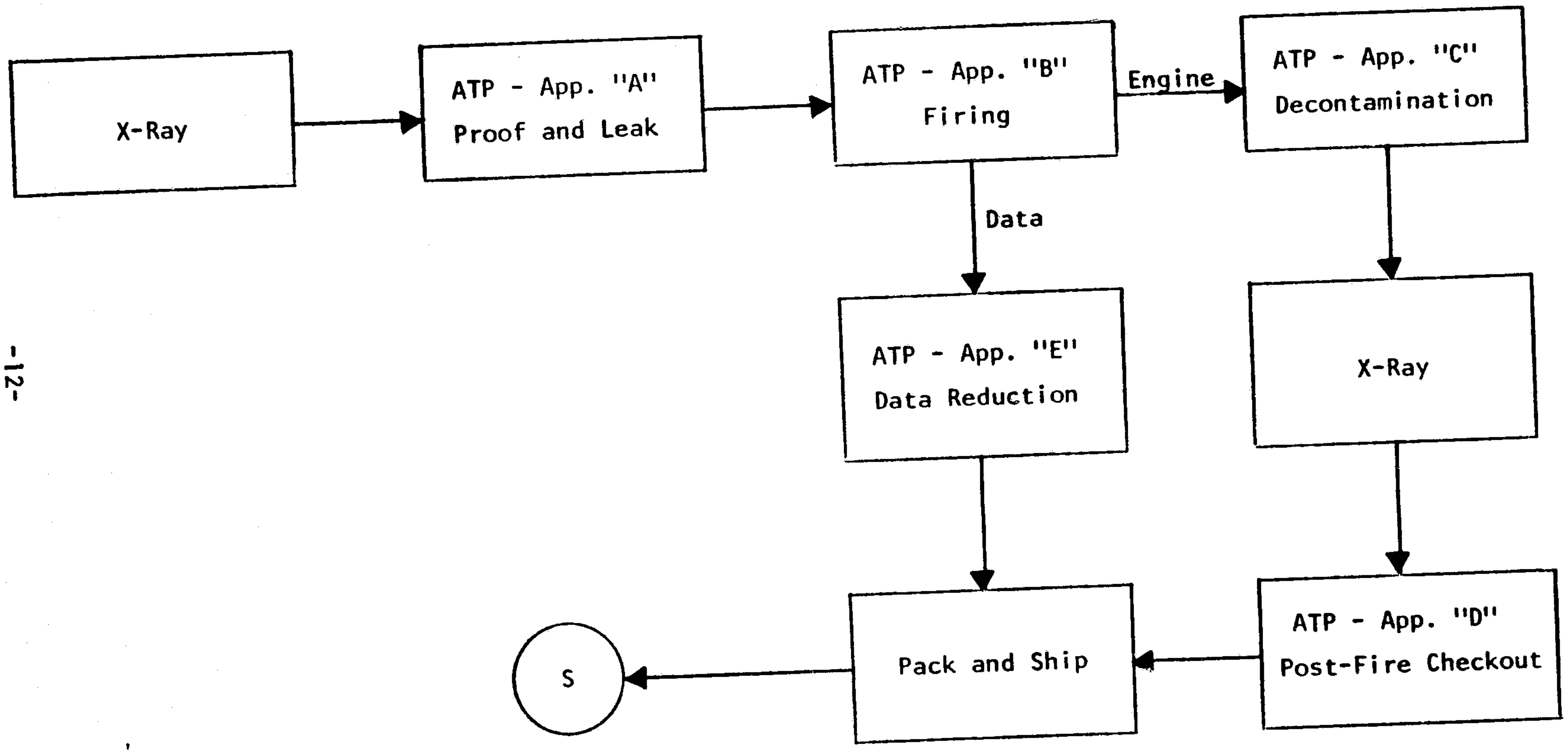
NOTES:

1. TP - App. "E" Standard Data Reduction was performed for each standard ATP-type firing and is reported in the Data Section

2. Rebuild of D204 to D204A was performed to provide NASA / JSC with an engine capable of extensive life testing at the APU level.

FIGURE 7

S/N D205 TEST SEQUENCE SUMMARY



1.3.1.2 Test Firing - Appendix "B" (continued)

ing the exhaust gas recirculation environment of the Auxiliary Power Unit installation. Exhaust gases from the ICGG were passed through a heat exchanger where the enthalpy removed simulated that absorbed in the APU turbine system. The gases were then recirculated around the gas generator housing before being finally exhausted to the atmosphere. The test duty cycle is shown in Table I and was identical to that used for previous Space Shuttle Gas Generator production hardware. The bootstrap start is simulated by setting the propellant tank ullage and pressurizing at a predetermined rate.

High speed oscillograph data acquisistion was controlled by an Automatic Test Control System (floppy disk type), which also controlled test system valving and test duty cycles.

1.3.1.3 Decontamination - Appendix "C"

The gas generators were fully decontaminated to remove all residual hydrazine prior to shipment.

1.3.1.4 Post-Fire Checkout - Appendix "D"

All electrical components: catalyst bed heater, temperature sensor, and pressure transducer, were subjected to electrical checks. For the pressure transducer this included a functional check at ambient pressure. The development thermocouples were also checked for continuity lead-to-lead and lead-to-body (gas generator). Interface requirements were re-inspected.

1.3.1.5 Data Reduction - Appendix "E"

Data was reduced and tabulated for each sequence of the firing.

GG PRODUCTION ACCEPTANCE TEST DUTY CYCLE

SEQ. NO.	RUN MODE	"ON" TIME SEC.	"OFF" TIME SEC	NO. of PULSES	EFFECTIVE STEADY STATE FLOW LB/SEC
1	Steady State	3	0	1	135 psia Start
2	Pulse	0.870	0.130	200	0.217
3	Pulse	0.110	0.890	200	0.217
4	Steady State	20	0	1	0.217
5	Pulse (PC Valve)	0.200	0.800	100	0.237
6	Pulse (SO Valve)	0.200	0.800	100	0.237
7	Steady State	20	0	1	0.237

TABLE 1

1.3.1.5 Data Reduction - Appendix "E" (continued)

Firing performance was compared to standard requirements for Space Shuttle Gas Generators.

1.3.2 Mission Duty Cycle Tests

Mission Duty Cycle Firings were used to accumulate life on S/N D204 in order to develop a life vs. performance comparison. To simplify testing, a streamlined firing sequence was used which accumulated approximately 71 minutes of firing (as described in Table II). A variety of duty cycles and a final steady state were used to add life while gathering performance data during these tests.

1.3.3 Hot Restart Tests

A total of 27 hot restarts were performed during the course of the test series, (22 on D204 and 5 additional on D204A). Warm-up runs for each series were 20 minutes long, (described in Table III). Restart and re-warming runs in a series were 4 minutes long (described in Table IV).

1.3.4 Overall Test Flow Plan

The hot restart/development testing performed on D204/D204A is shown in Figure 6. The conditions for the hot restarts, test series 1, 2, 2R, 3 and 1' are listed in Tables V through IX.

The sequence of testing performed on S/N D205 is shown in Figure 7.

TABLE II

S.S. G.G. MISSION DUTY CYCLE

SEQUENCE	Seq. Time Sec.	No Pulses	ON Time Sec.	OFF Time Sec.	% D.C	PROP. TANK		GGVM		Test Times
						Main	Hoke	P.C.	S.O.	
1. (Bootstrap Start)	3	1	3	-	100	X				3
2.	1050	1050	.16	.84	16	X		X		1053
3.	1050	1050	.20	.80	20	X		X		2103
4.	1050	1050	.24	.76	24	X		X		3153
5.	1050	1050	.30	.70	30	X		X		4203
6.	20	1	20	0	100	X		X		4223

TABLE III

S.S. G.G. HOT RESTART PREHEAT DUTY CYCLE

SEQUENCE	Seq. Time Sec.	No. Pulses	ON Time Sec.	OFF Time Sec.	% D.C.	PROP. TANK		GGVM		Test Times Sec.
						Main	Hoke	P.C.	S.O.	
1. (Bootstrap)	5	1	5	0	100	X			X	5
2.	1080	1080	.2	.8	20	X		X		1085
3.	100	100	.8	.2	80	X		X		1185
4.	20	1	20	0	100	X		X		1205

TABLE IV

S.S. G.G. HOT RESTART RE-HEAT DUTY CYCLE

SEQUENCE	Seq. Time Sec.	No. Pulses	ON Time Sec.	OFF Time Sec.	% D.C.	PROP. TANK		GGVM		Test Times Sec.
						Main	Hoke	P.C.	S.O.	
1. (Bootstrap)	5	1	5	0	100		X		X	5
2.	120	120	.2	.8	20	X		X		125
3.	100	100	.8	.2	80	X		X		225
4.	20	1	20	0	100	X		X		245

TABLE V

HOT RESTART SERIES 1

D204

FIRING NO.	SOAKBACK TIME	P_f (psia)	T_f (°F)
0	-	130	Amb.
1	30 Minutes	400	≥ 150
2	30 Minutes	200	≥ 150
3	30 Minutes	100	≥ 150
4	10 Minutes	400	≥ 150
5	10 Minutes	200	≥ 150

TABLE VI

HOT RESTART SERIES 2

D204

FIRING NO.	SOAKBACK TIME	P_f (psia)	T_f (°F)
0'	-	130	Amb.
6	30 Minutes	400	$\geq$150
7	10 Minutes	200	$\geq$150

TABLE VII

HOT RESTART SERIES 2R

D204

FIRING NO.	SOAKBACK TIME	P_f (psia)	T_f (°F)
0''	-	130	Amb.
6'	10 Minutes	100	≥150
7'	5 Minutes	400	≥150
8	5 Minutes	200	≥150
9	5 Minutes	100	≥150
10	2 Minutes	400	≥150
11	2 Minutes	200	≥150
12	2 Minutes	100	≥150
13	2 Minutes	90	≥150
14	2 Minutes	80	≥150
15	90 Seconds	80	≥150

TABLE VIII

HOT RESTART SERIES 3

D204

FIRING NO.	SOAKBACK TIME	P_f (psia)	T_f (°F)
0'''	-	130	Amb.
16	60 Seconds	80	≥ 150
17	45 Seconds	80	≥ 150
18	30 Seconds	80	≥ 150
19	15 Seconds	80	≥ 150
20	7 Seconds	80	≥ 150

TABLE IX

HOT RESTART SERIES 1'

D204A

FIRING NO.	SOAKBACK TIME	P_f (psia)	T_f (°F)
0''''	-	130	Amb.
1'	10 Minutes	400	$\geq$ 150
2'	10 Minutes	200	$\geq$ 150
3'	5 Minutes	400	$\geq$ 150
4'	2 Minutes	400	$\geq$ 150
5'	2 Minutes	80	$\geq$ 150

2.0 DATA REVIEW AND DISCUSSION

In this section, the data retrieved from the testing is reviewed and discussed. Viable explanations for any unusual test behavior are presented and examined.

2.1 ATP DATA REDUCTION

The standard data reduction for Space Shuttle Gas Generator ATP's includes response and tailoff time in pulse mode operation, and peak-to-peak roughness, normalized chamber pressure, normalized gas temperature in steady state operation. The pressure budget for the feed system is also calculated and temperature sensor readings are recorded for each sequence)information only). Table X defines the method of determining each parameter, acceptance criteria, and a nominal range for earlier (Minor Modification and Active Cooling) Gas Generators. Table XI lists the data from the ATP's performed on S/N's D204, D204A and D205. The roughness has been reported in two ways. The average roughness is characterized by the peak-to-peak magnitude of continuous, cyclic chamber pressure variations. The maximum roughness is recorded as the peak-to-peak magnitude of the greatest chamber pressure variation during the last 2 seconds of steady state.

The ATP firings were used as a performance standard throughout the testing. When deterioration in the catalyst bed occurs, it is noted by a marked increase in roughness (peak-to-peak chamber pressure variation), and is usually accompanied by a lengthening of tailoff time in chamber pressure at the end of a pulse. Gas temperature often increases with bed deterioration as NH_3 dissociation, which is endothermic, decreases due to channeling of gases through voids in the bed.

TABLE X

ATP DATA REDUCTION

PARAMETER	SEQUENCE APPLIED TO	REDUCTION METHOD	ACCEPTANCE CRITERIA	NOMINAL RANGE MEAN $\pm$ 10
Response Time	5	Time from first Pc rise until Pc reaches 945 psig	$50\ ^{+30}_{-50}$ ms	45 / 61 ms
	6		$50\ ^{+30}_{-50}$ ms	43 / 62 ms
Tailoff Time	5	Time from first drop in feed pressure until chamber pressure has fallen to 90 psig.	$\leq$ 120 ms	82 / 95 ms
	6		$\leq$ 120 ms	90 /100 ms
Roughness	4	Average peak-to-peak roughness in the last 23 seconds of each sequence.	$\leq$ 40 psi	10 / 22 psi
	7		$\leq$ 40 psi	10 / 19 psi
Gas Temperature (Normalized)	4	$T_{G(Norm)} = T_{G(Meas)} \times \left(\frac{.217}{\bar{\dot{w}}}\right)^{.083}$	1669-1736°F	1092 / 1717
	7	$T_{G(Norm)} = T_{G(Meas)} \times \left(\frac{.237}{\bar{\dot{w}}}\right)^{.083}$	1681-1748°F	1708 / 1735
Chamber Pressure (Normalized)	4	$P_{c(Norm)} = P_{c(Meas)} \times \left(\frac{.217}{\bar{\dot{w}}}\right)$	1031-1105 psia	1064 / 1090 psia
	7	$P_{c(Norm)} = P_{c(Meas)} \times \left(\frac{.237}{\bar{\dot{w}}}\right)$	1123-1203 psia	1166 / 1192 psia
Feed Pressure Budget	4	$\text{Pressure Budget} = \frac{P_{f(Meas)} - P_{c(Meas)}}{P_{c(Norm)}}$	$\leq$ 0.32	.21 / .26

TABLE XI

ATP DATA ICGG TESTING

S/N	TEST	RESPONSE		TAILOFF		ROUGHNESS (AVE.)		ROUGHNESS (MAX)	
		Seq. 5	Seq. 6	Seq. 5	Seq. 6	Seq. 4	Seq. 7	Seq. 4	Seq. 7
D204	ATP-1	51	55	86	94	30	27	42	39
D204	ATP-2	59	58	94	100	24	24	27	30
D204	ATP-3	58	54	109	115	66	90	126	186
D204A	ATP-1	52	52	83	97	18	27	27	33
D204A	ATP-2	50	52	80	90	18	21	24	27
D205	ATP-1	43	58	87	97	18	18	42	48

TABLE XI (continued)

S/N	TEST	P_c (NORM) PSIA		T_G (NORM) °F		PRESSURE BUDGET
		Seq. 4	Seq. 7	Seq. 4	Seq. 7	
D204	ATP-1	1082	1184	1672	1687	0.22
D204	ATP-2	1078	1179	1678	1697	0.24
D204	ATP-3	1073	1171	1697	1717	0.25
D204A	ATP-1	1077	1173	1699	1718	0.24
D204A	ATP-2	1077	1181	1665	1684	0.23
D205	ATP-1	1089	1184	1678	1690	0.23

2.2 S/N D204

The initial firing of S/N D204 showed operation very similar to the Minor Modification Gas Generators, though the maximum roughness was higher than expected. An examination of some pulses (Figure 8) shows that the engine exhibited some Pc irregularities that are more severe than commonly seen in Minor Modification/Active Cooling production acceptance tests, (see Figure 9 pulses from Active Cooling Unit S/N 3007 ATP). Note that despite the somewhat different pulse shape, both the response and tailoff times were well within the family.

Gas temperature was somewhat lower than for Minor Modification Units but was within the Minor Modification acceptance criteria. A lower gas temperature was expected and in fact planned for as the bed had been lengthened to increase life and the lower bed loading resulted in a longer residence time which in turn allowed for additional NH_3 dissociation in the bed. At the uprated flowrate of 0.265 lbm/sec., the gas temperature for the ICGG should be approximately 1700°F.

After the initial ATP firing, Mission Duty Cycles 1, 2, and 3 were accumulated on the generator. During the course of those firings, the roughness dropped slightly and the pulse shapes appeared more normal. There was some rise in gas temperature from test to test as shown in Table XII. At the end of the first three MDC firings, 3.7 hours had been accumulated on the gas generator without performance degradation.

Reference ATP-2 was fired next. All parameters were acceptable and close to the nominal values for a Space Shuttle APU Gas Generator. The pulse shapes (Figure 10) more closely resembled those normally seen on earlier units.

The Hot Restart Tests on S/N D204 were run in four series (Tables V, VI, VII, and VIII). The data for both S/N D204 and S/N D204A hot

SPACE SHUTTLE APU GAS GENERATOR
TYPICAL PULSES
ATP-1
S/N D204 (ICGG)

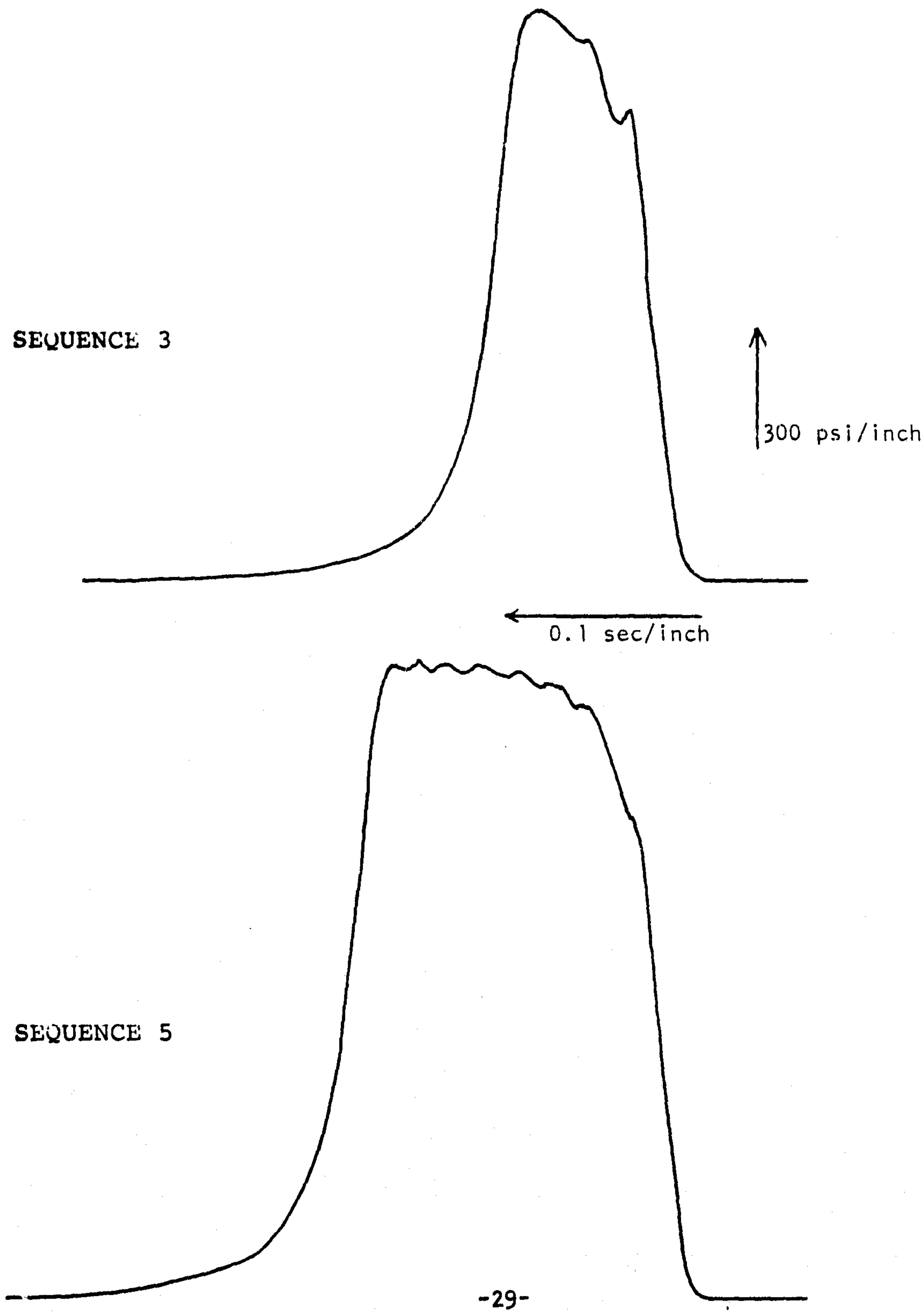


FIGURE 8

SPACE SHUTTLE APU GAS GENERATOR
TYPICAL PULSES
ATP-1
S/N 3007 (A/C)

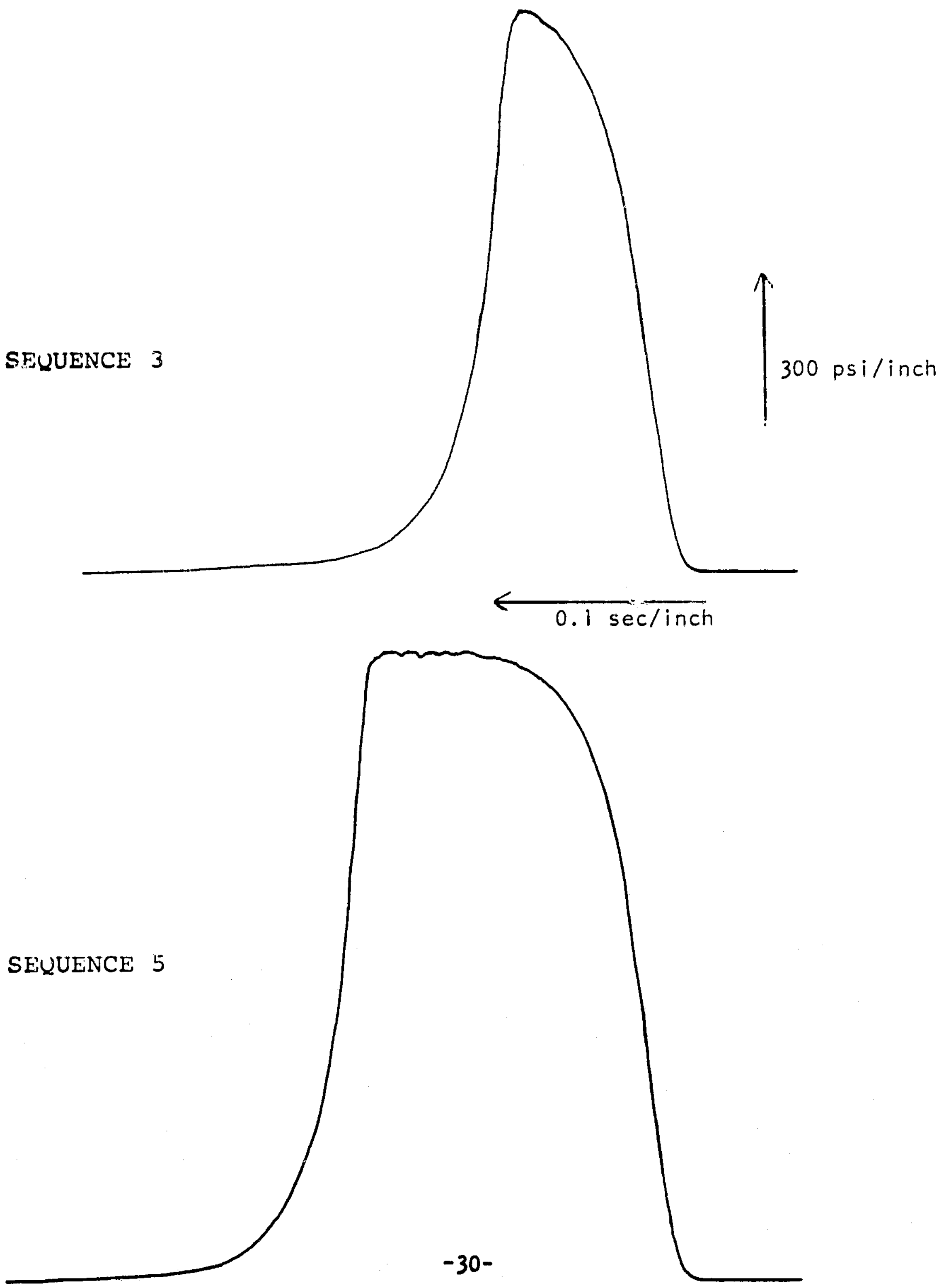


FIGURE 9

TABLE XII

MDC DATA

M D C	$\dot{w}$	$T_{(GAS)}$		ROUGHNESS	
		Meas.	Norm. to $\dot{w}$ = .237	Ave.	Max.
1	.23424	1690	1692	24	37
2	.23486	1695	1696	27	33
3	.23431	1700	1702	18	21
4	.2323	1710	1713	108	195

SPACE SHUTTLE APU GAS GENERATOR
TYPICAL PULSES
ATP-2
S/N D204 (ICGG)

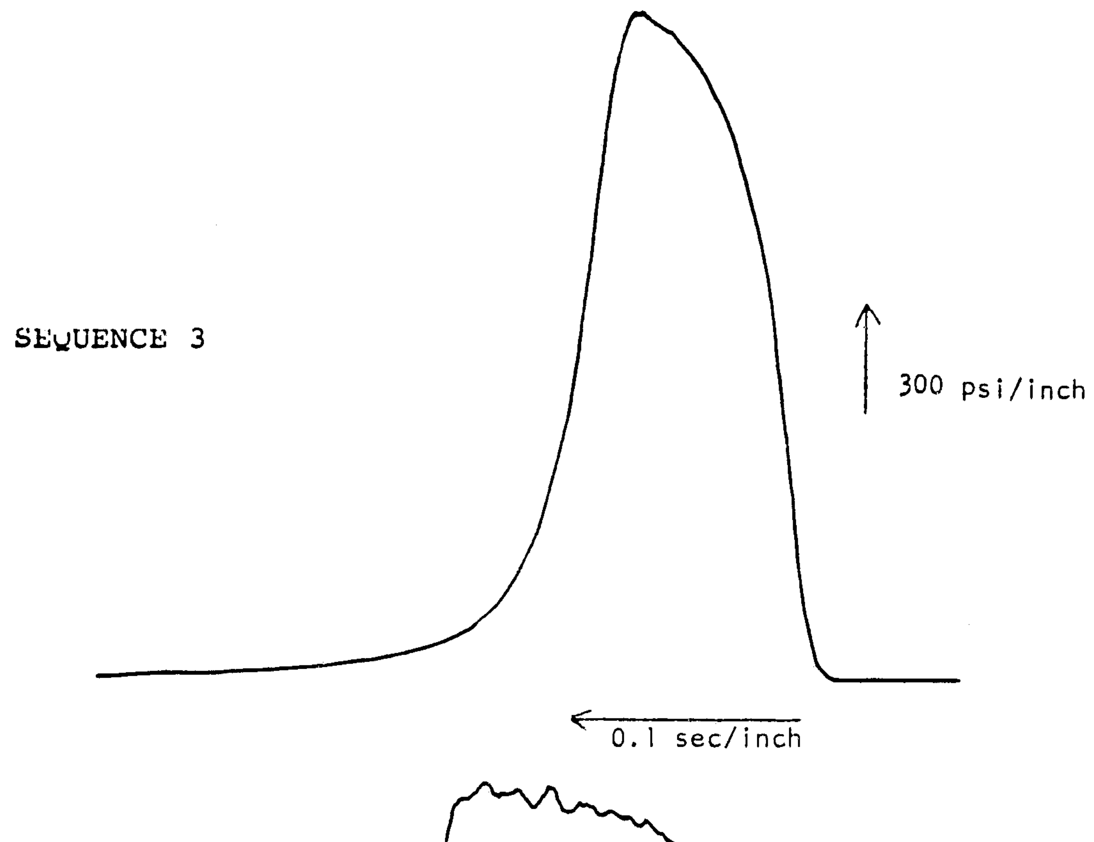


FIGURE 10

2.2 S/N D204 (continued)

restart testing is summarized in Table XIII. The Pc listed is for the final steady state. The response and tailoff times are from the 12th pulse in each run. For hot restarts where an initial pressure overshoot occurred, the steepest slope of that rise to that overshoot is recorded in psi/sec. Overshoot is the pressure level at the peak above the pressure level following the peak. The surge flowrate is the maximum value of the initial flow surge into the generator.

The initial series of runs showed some significant overshoots on restart between 243 and 534 psi, but examination of the oscillograph record and a review of the test control system showed:

- The feed tank enable valve received its signal to open simultaneously with the GGVM. Due to the relatively rapid response of the GGVM and the system volume there was a period of approximately 40 ms during which the GGVM was open with zero feed pressure. After 40 ms, the feed system rapidly pressurized resulting in surge fuel flow into the gas generator. (Pc overshoots for hot restarts 1 - 5 are shown in Figures 11 through 15. Plots of flowrate versus time during restarts 1, 2, and 3 are shown in Figures 16, 17 and 18). The rather high Pc overshoots on these starts appear to have resulted from the surge flow into the bed caused by the valve sequencing anomaly. It was decided to re-run the conditions of restarts 1 and 5 before continuing, and Runs 6 and 7 (Series 2) were performed to accomplish this. There was still a valve sequencing error in Runs 6 and 7, but the effect was an instantaneous (~5ms) feed pressure of approximately 800 psi on Restart 7 which rapidly decayed to the planned start pressure of 200 psig. This valving anomaly was corrected before any additional runs were made, but there was still considerable surge flow on these runs. As Table XIII indicates, Restart 6 had a Pc overshoot about as severe as Restart 1, while Restart 7 was less severe than Restart 5, which it was intended to repeat.

TABLE XIII

D204 AND D204A HOT RESTART TEST DATA

SERIES #	RUN #	RESPONSE (ms)	TAILOFF (ms)	ROUGHNESS (PSI)		P_c (psia)	OVERSHOOT (psia)	RISE RATE (psi/sec)	FEED PRESSURE (psi)	SURGE FLOWRATE (lbm /sec)
				Average	Maximum					
1	0	55	96	18	NA	1170	-	-	-	-
1	1	50	95	18	NA	1117	243	27K	400	0.172
1	2	56	100	21	NA	1162	255	15K	200	0.191
1	3	54	99	18	NA	1156	294	32.7K	100	0.191
1	4	52	101	18	NA	1155	366	40.7K	400	0.191
1	5	51	97	18	NA	1155	534	99.7K	200	0.202
2	0'	50	95	18	36	1170	-	-	-	-
2	6	48	100	27	63	1119	249	31.1K	400	0.130
2	7	50	100	NA	NA	NA	258	32.2K	200	0.139
2R	0''	56	105	33	57	1177	-	-	-	-
2R	6'	54	103	24	48	1171	-	-	100	0.074
2R	7'	53	102	21	39	1171	324	23.1K	400	0.129
2R	8	56	105	42	75	1173	-	-	200	0.092
2R	9	54	110	39	60	1173	-	-	100	0.071
2R	10	53	112	24	42	1174	450	30K	400	0.126
2R	11	53	111	33	54	1176	-	-	200	0.097

TABLE XIII (continued)

SERIES #	RUN #	RESPONSE (ms)	TAILOFF (ms)	ROUGHNESS (PSI)		P_c (psia)	OVERSHOOT (psia)	RISE RATE (psi/sec)	FEED PRESSURE (psi)	SURGE FLOWRATE (lbm /sec)
				Average	Maximum					
2R	12	48	112	24	48	1174	-	-	100	0.071
2R	13	55	107	30	42	1174	-	-	90	0.064
2R	14	54	110	33	48	1173	-	-	80	0.071
2R	15	51	110	30	63	1170	-	-	80	0.074
3	0'''	48	116	72	93	1158	-	-	-	-
3	16	45	105	63	126	1152	-	-	80	0.071
3	17	42	106	75	138	1158	-	-	80	0.071
3	18	43	105	87	132	1159	-	-	80	0.068
3	19	45	105	93	141	1167	-	-	80	0.071
3	20	47	110	96	159	1167	-	-	80	0.071
1'	0	45	89	18	33	1150	-	-	-	-
1'	1	44	83	15	24	1152	93	5.5K	400	0.130
1'	2	43	82	15	33	1155	-	-	200	0.092
1'	3	41	85	18	30	1158	51	3.9K	400	0.121
1'	4	41	85	12	18	1152	-	-	400	0.119
1'	5	45	84	18	18	1144	-	-	80	0.071

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 1
S/N D204 RUN 1
BOOTSTRAP STARTUP

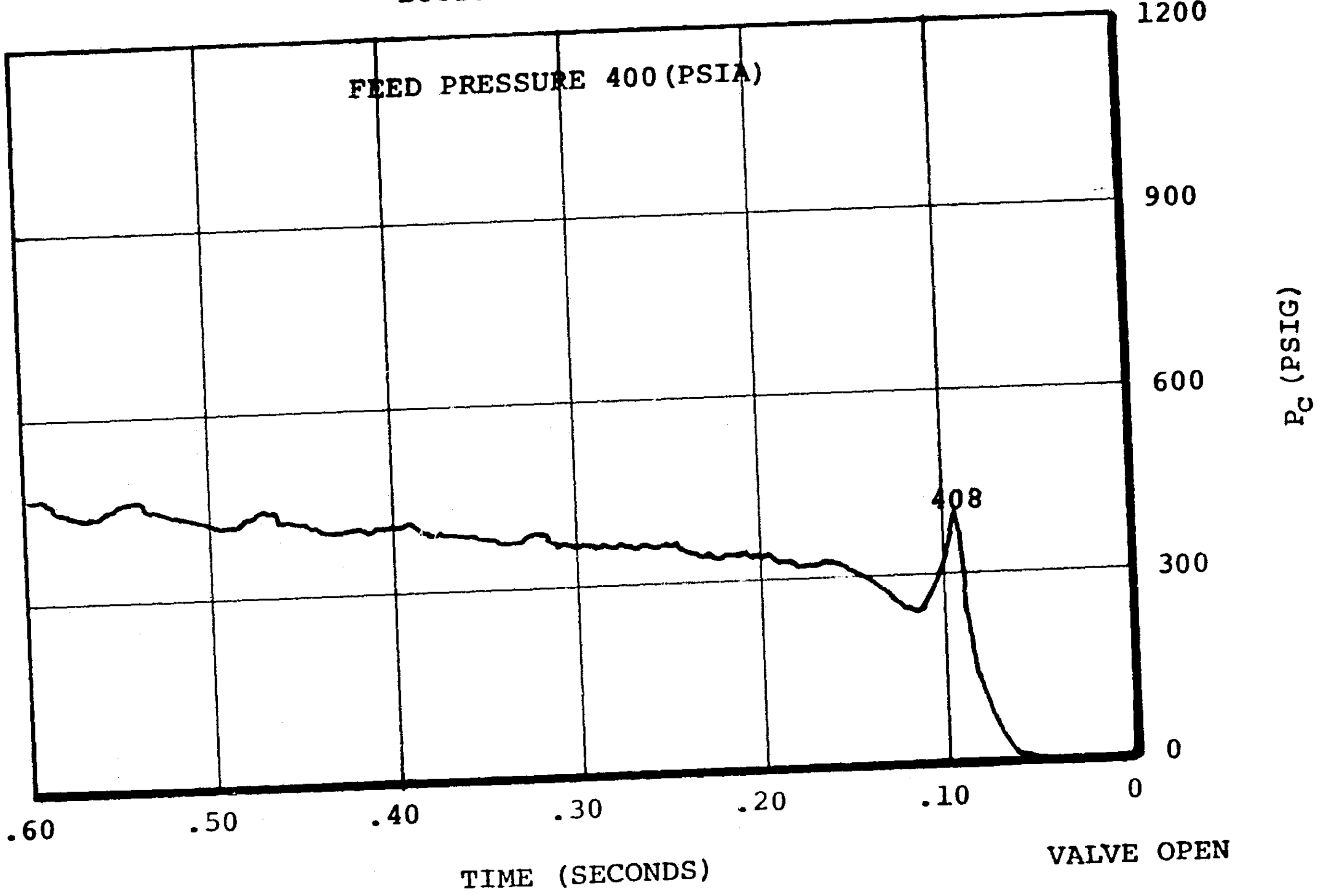


FIGURE 11

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 1
S/N D204 RUN 2
BOOTSTRAP STARTUP

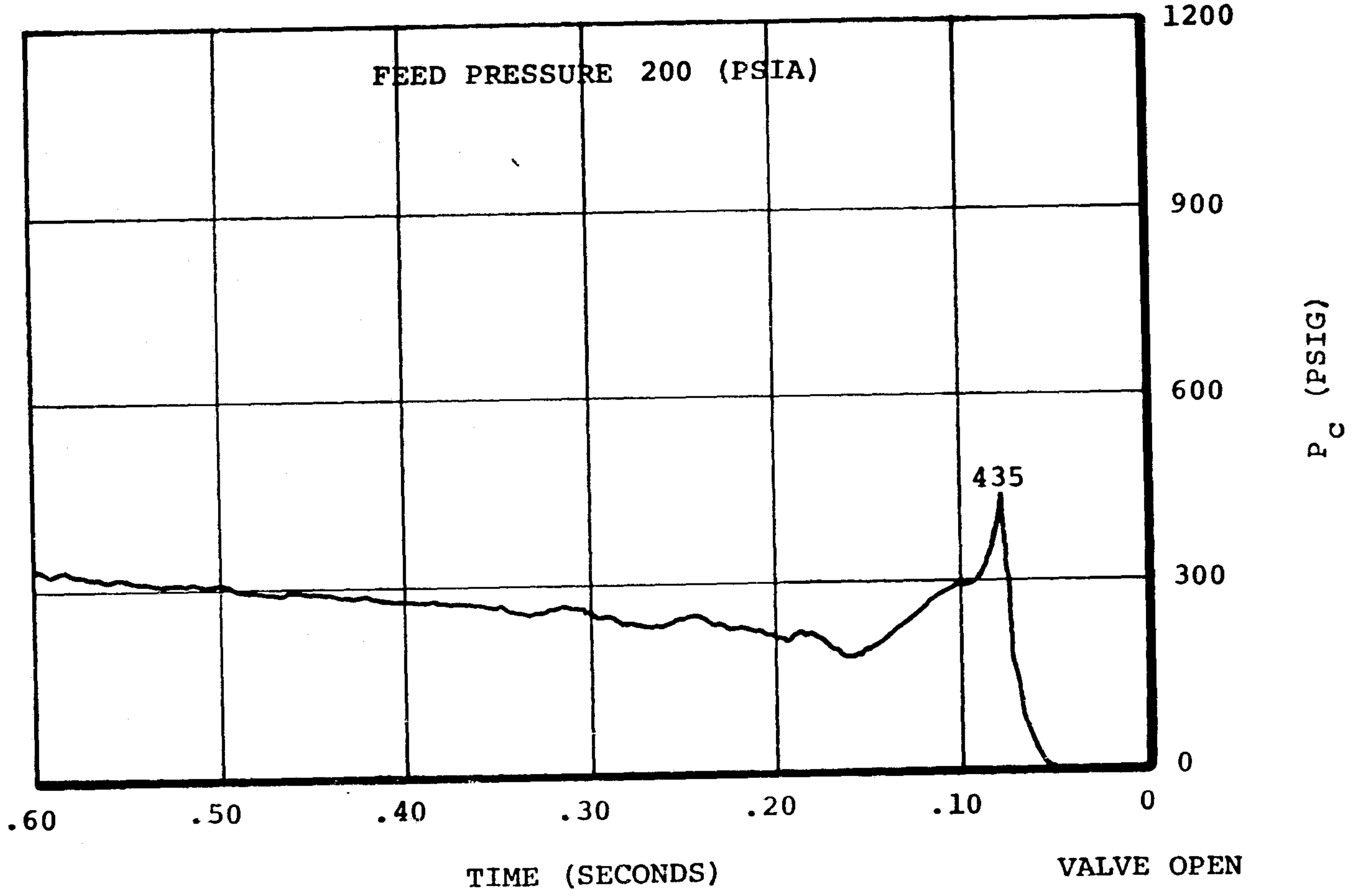


FIGURE 12

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 1
S/N D204 RUN 3
BOOTSTRAP STARTUP

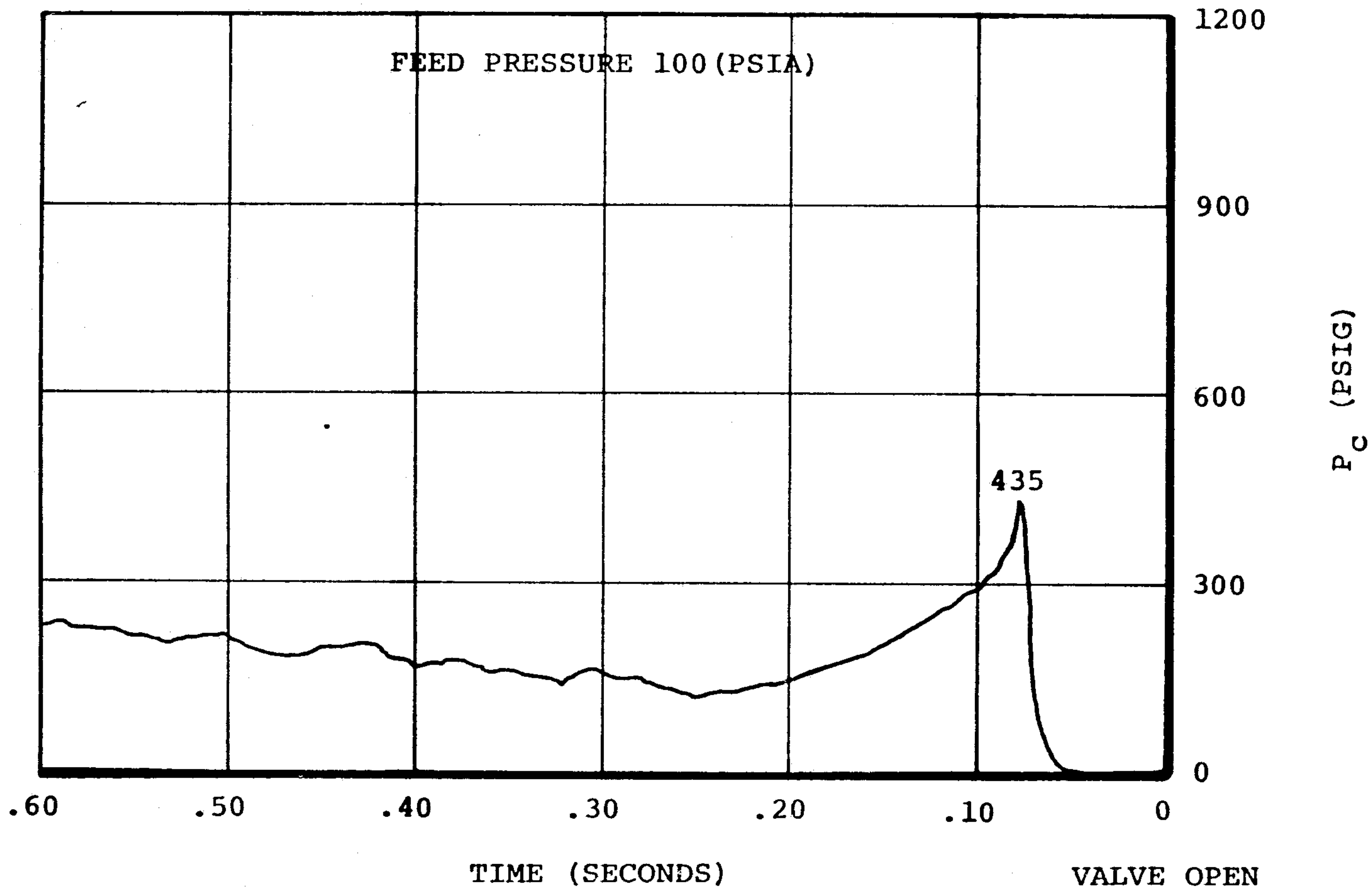


FIGURE 13

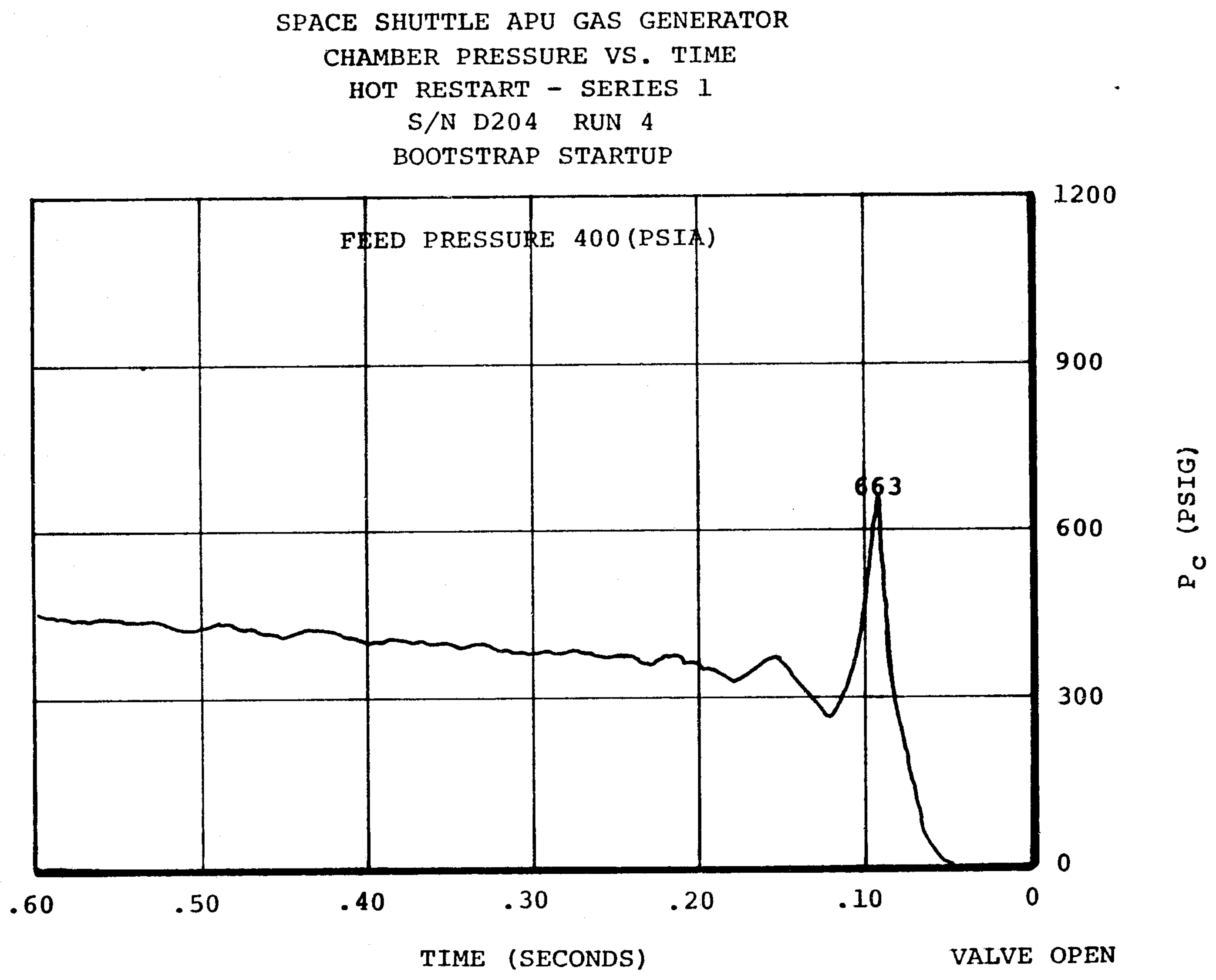

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 1
S/N D204 RUN 4
BOOTSTRAP STARTUP
FEED PRESSURE 400(PSIA)
663
1200
900
600
300
0
P_c (PSIG)
.60
.50
.40
.30
.20
.10
0
TIME (SECONDS)
VALVE OPEN

FIGURE 14

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 1
S/N D204 RUN 5
BOOTSTRAP STARTUP

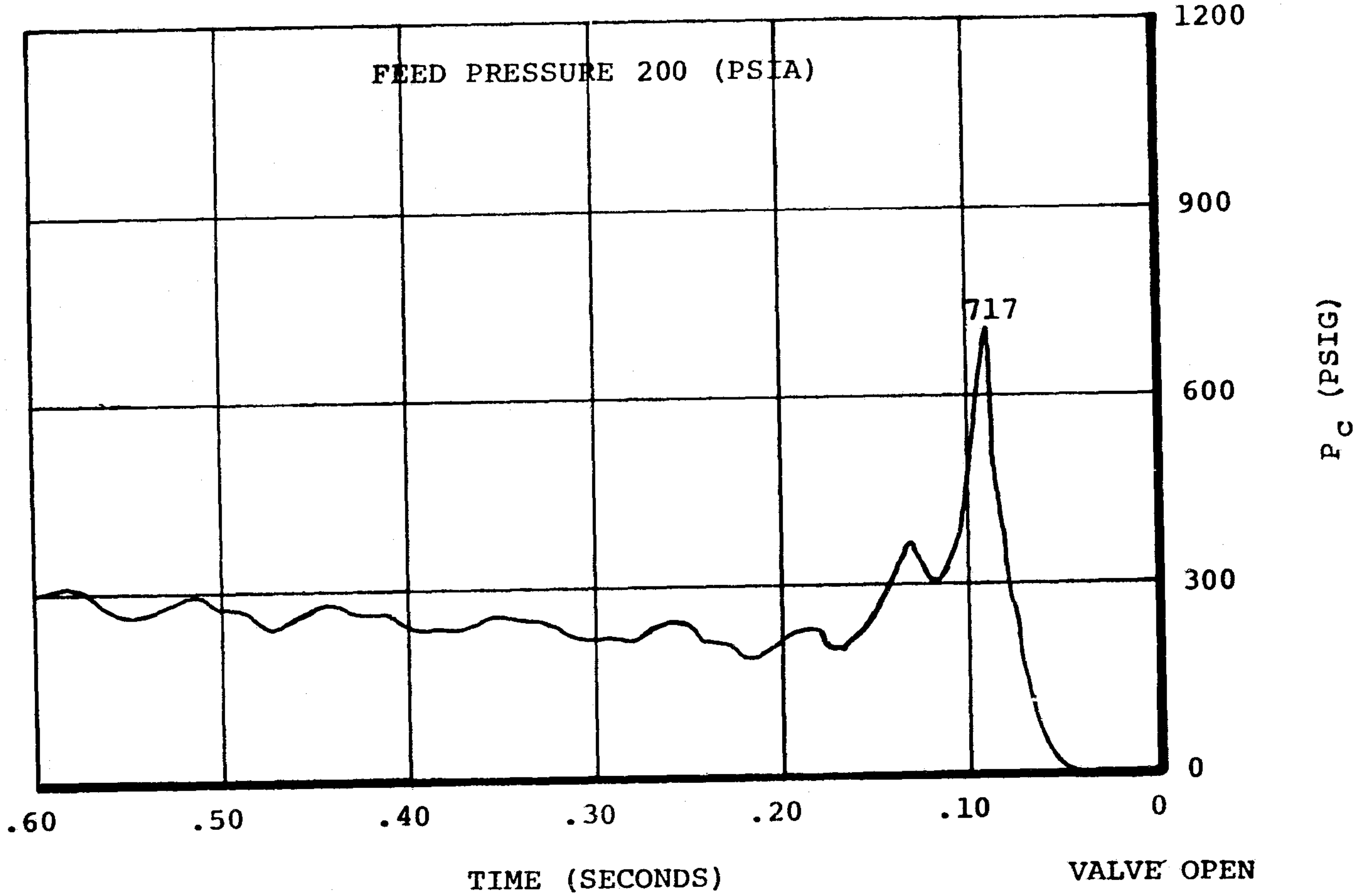
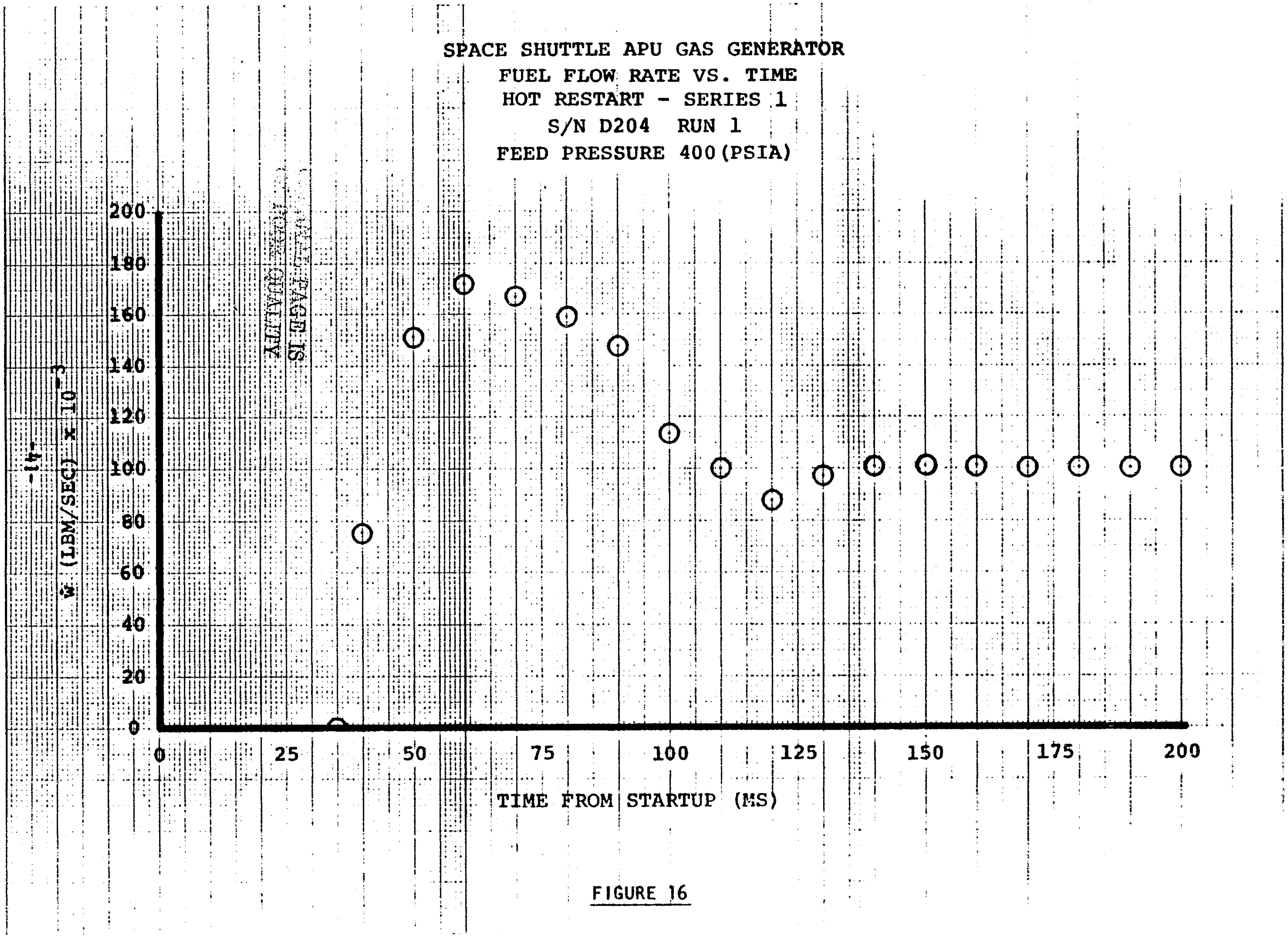


FIGURE 15



SPACE SHUTTLE APU GAS GENERATOR
FUEL FLOW RATE VS. TIME
HOT RESTART - SERIES 1
S/N D204 RUN 1
FEED PRESSURE 400 (PSIA)
200
180
160
140
120
100
80
60
40
20
0
$\dot{w}$ (LBM/SEC) x 10^{-3}
0
25
50
75
100
125
150
175
200
TIME FROM STARTUP (MS)

FIGURE 16

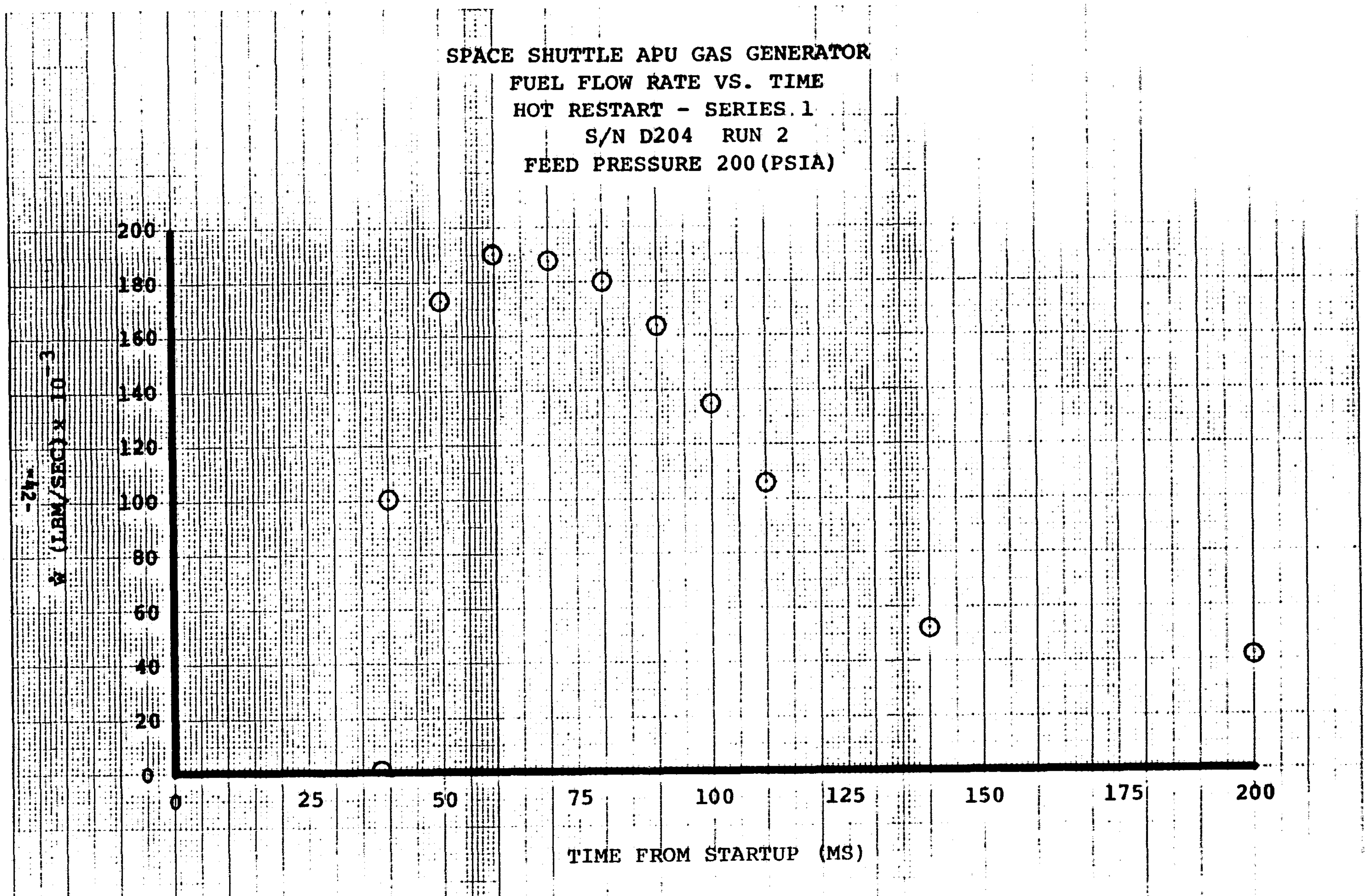

SPACE SHUTTLE APU GAS GENERATOR
FUEL FLOW RATE VS. TIME
HOT RESTART - SERIES 1
S/N D204 RUN 2
FEED PRESSURE 200 (PSIA)
ẇ (LBM/SEC) x 10^-3
200
180
160
140
120
100
80
60
40
20
0
0
25
50
75
100
125
150
175
200
TIME FROM STARTUP (MS)

FIGURE 17

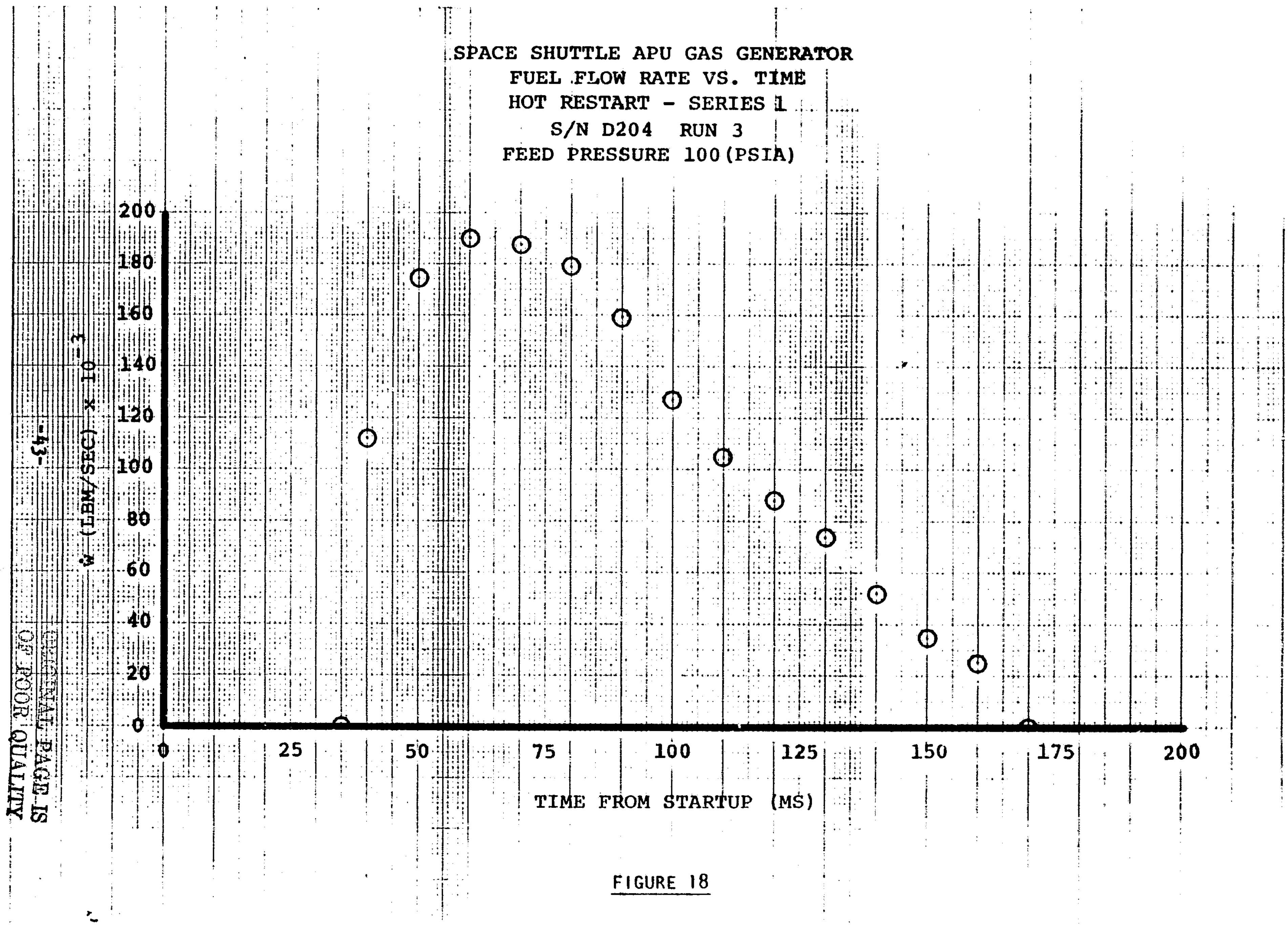

SPACE SHUTTLE APU GAS GENERATOR
FUEL FLOW RATE VS. TIME
HOT RESTART - SERIES 1
S/N D204 RUN 3
FEED PRESSURE 100 (PSIA)
ẇ (LBM/SEC) x 10^-3
200
180
160
140
120
100
80
60
40
20
0
0
25
50
75
100
125
150
175
200
TIME FROM STARTUP (MS)

FIGURE 18

2.2 S/N D204 (continued)

The planned test was continued with Series 2R. The only overshoots in this series appeared on runs with initial inlet pressures of 400 psig (Runs 7' and 10, Figures 19 and 20). Surge flow into the bed again appeared to be the cause of the overshoots. On a number of the low pressure starts, severe chamber pressure oscillations were noted (See Figures 21 and 22), and considerable coupling with the feed system was indicated, but initial flow surges were of smaller magnitude and no overshoots were noted. On the runs with protracted pressure oscillations of sizable amplitude, it was noted that the fuel pressure (P_f) follows Pc with a very slight delay (~5ms) and appreciable damping. The fuel flow as indicated by the Ramapo (momentum type) also showed flow oscillations out of phase with Pc ($\dot{w}$ dropped as Pc peaked). Such oscillations were to be expected and were undoubtedly the cause of the subsequent drop in Pc which allowed flow to rise. Oscillations decreased as the increasing feed pressure, during bootstrap, resulted in a harder feed system which was not as strongly affected by chamber pressure variation. It was noted (Table XIII) that roughness increased from series to series. The roughness was not high enough at that point to cause concern, but the sudden increase appeared unusual.

A comparison was made of the thermal margin model predictions for cases with maximum valve soakback and maximum branch tube soakback temperatures at restart. Though some differences appeared in the way thermal margin varied with time, the maximum branch tube temperature condition appeared slightly more severe. We did not apply a large enough amount of heat to the valve to reach the maximum predicted valve soakback temperatures, but did reach temperatures at the valve comparable to those predicted when the branch tube temperatures peaked. The worst case hot restart tests were therefore those run at maximum branch tube temperatures and should represent a realistic worst-case for the APU.

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 2R
S/N D204 RUN 7
BOOTSTRAP STARTUP

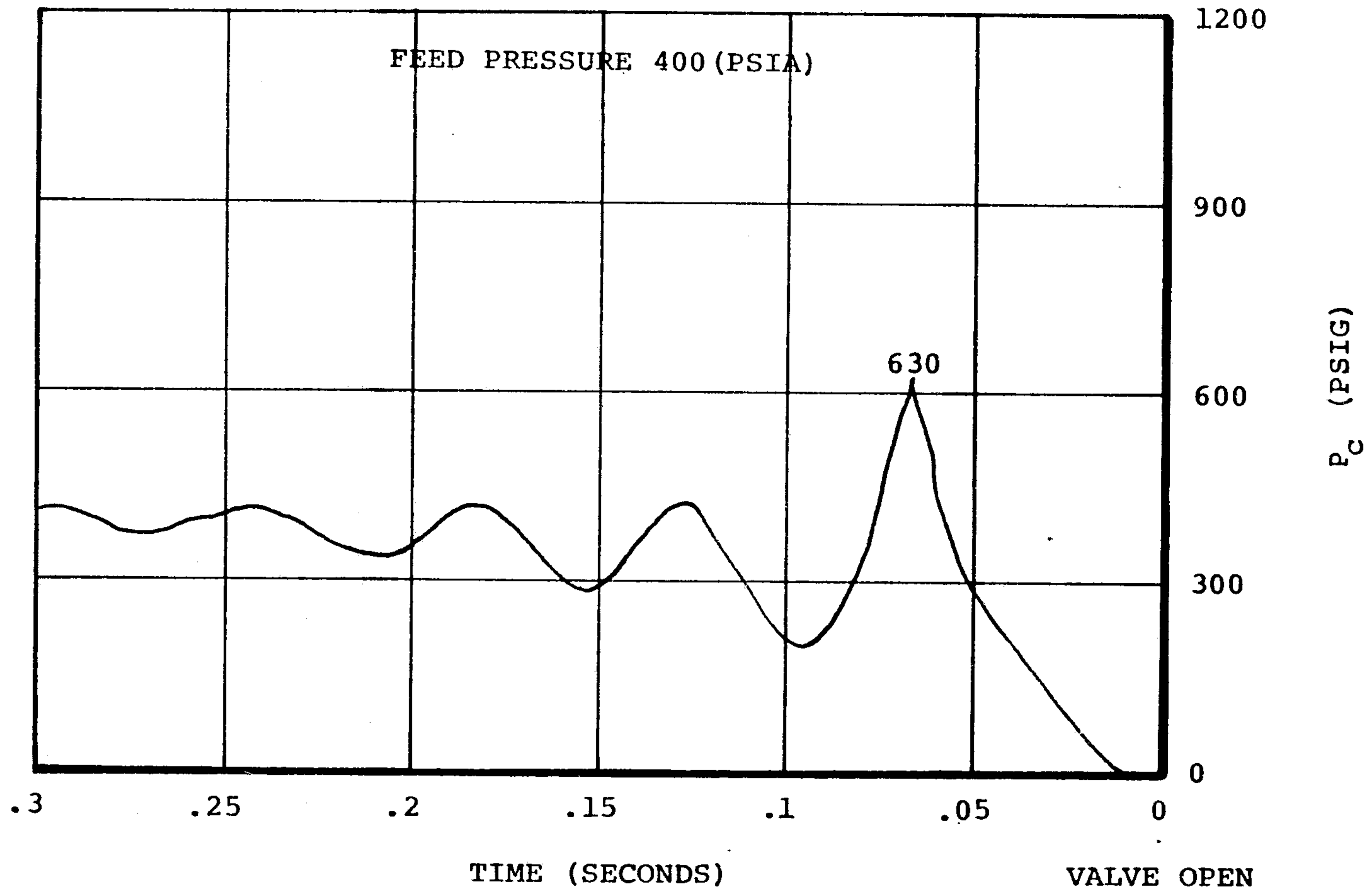


FIGURE 19

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 2R
S/N D204 RUN 10
BOOTSTRAP STARTUP

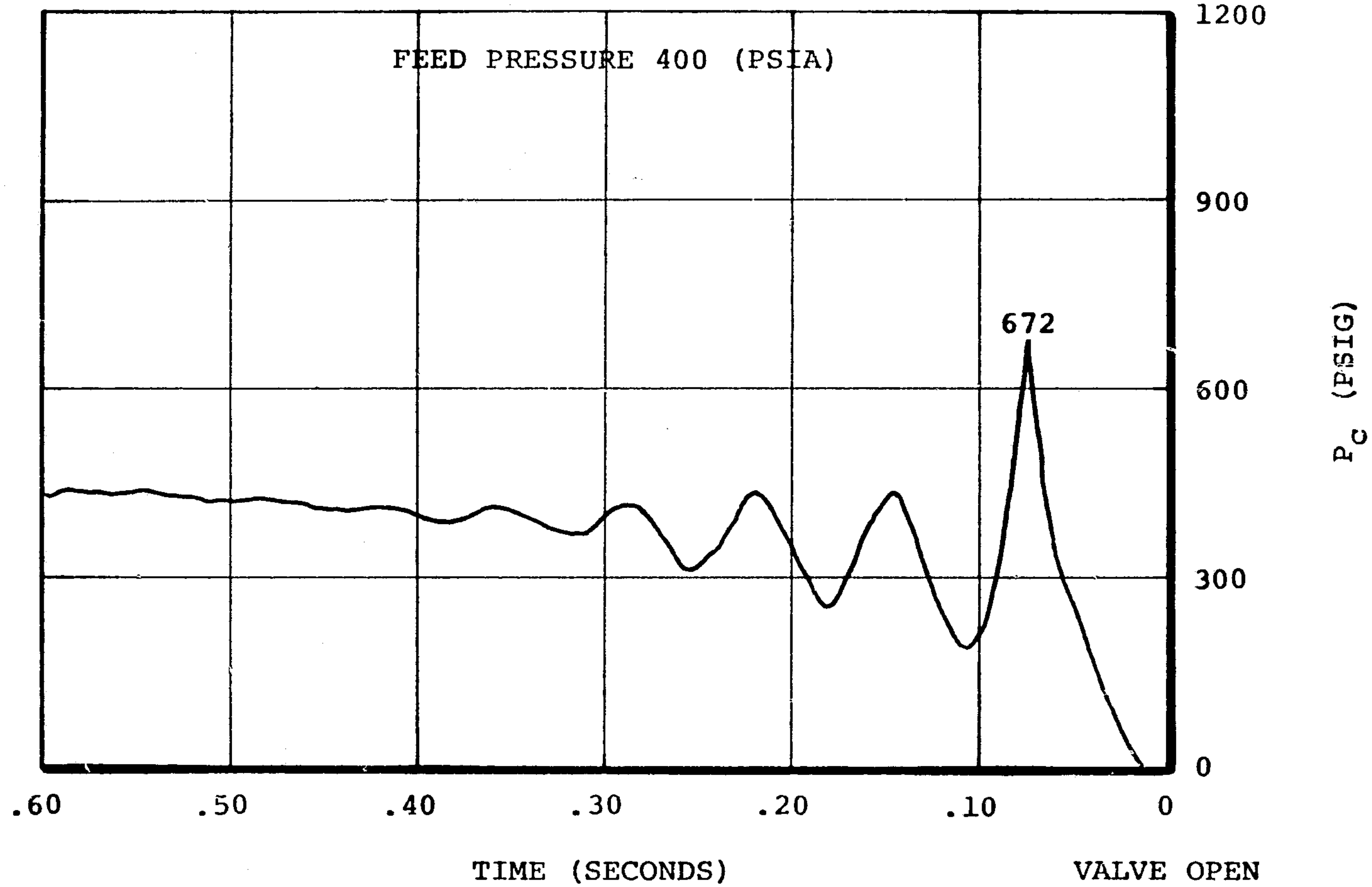


FIGURE 20

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 2R
S/N D204 RUN 12
BOOTSTRAP STARTUP

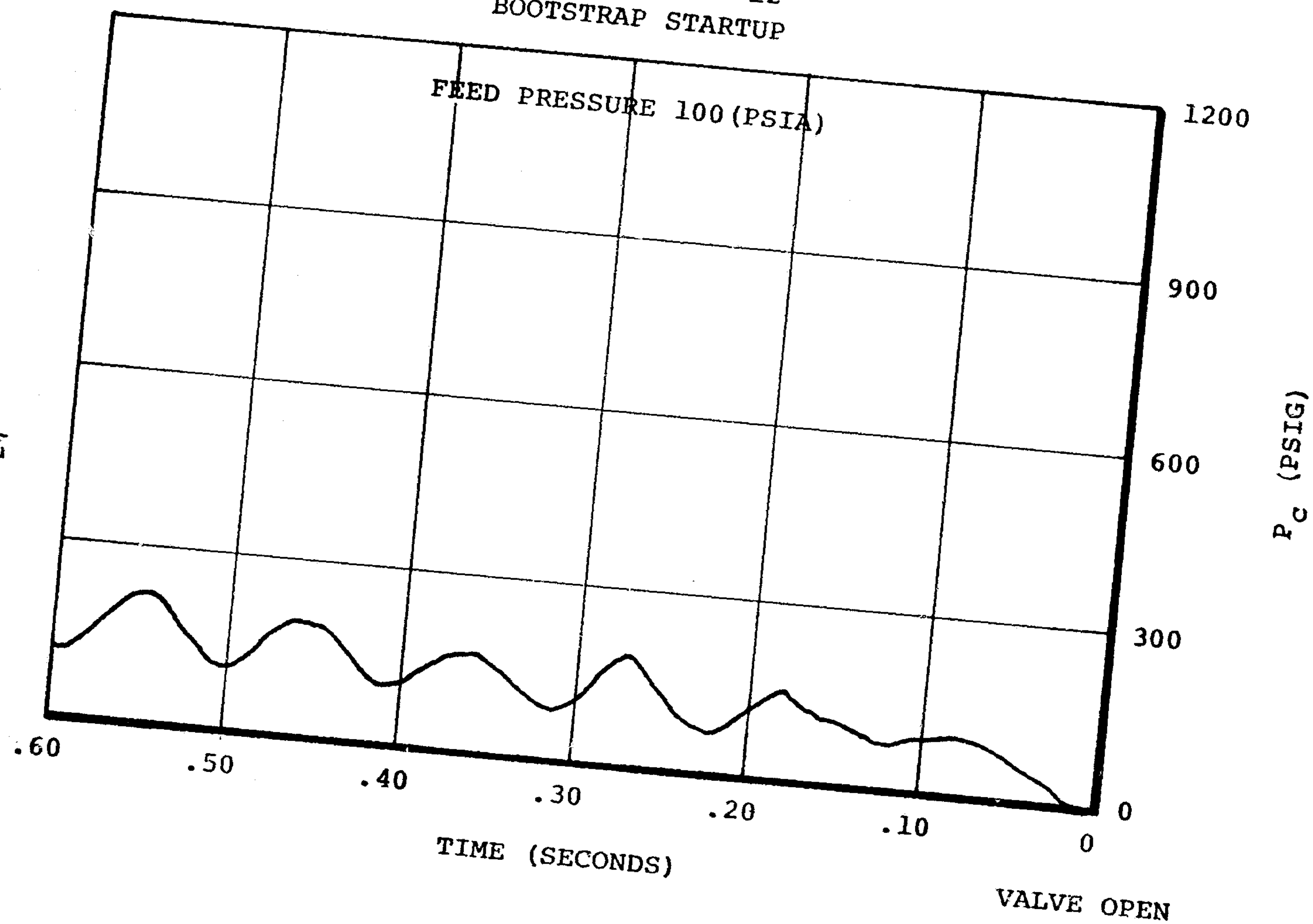


FIGURE 21

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 2R
S/N D204 RUN 13
BOOTSTRAP STARTUP

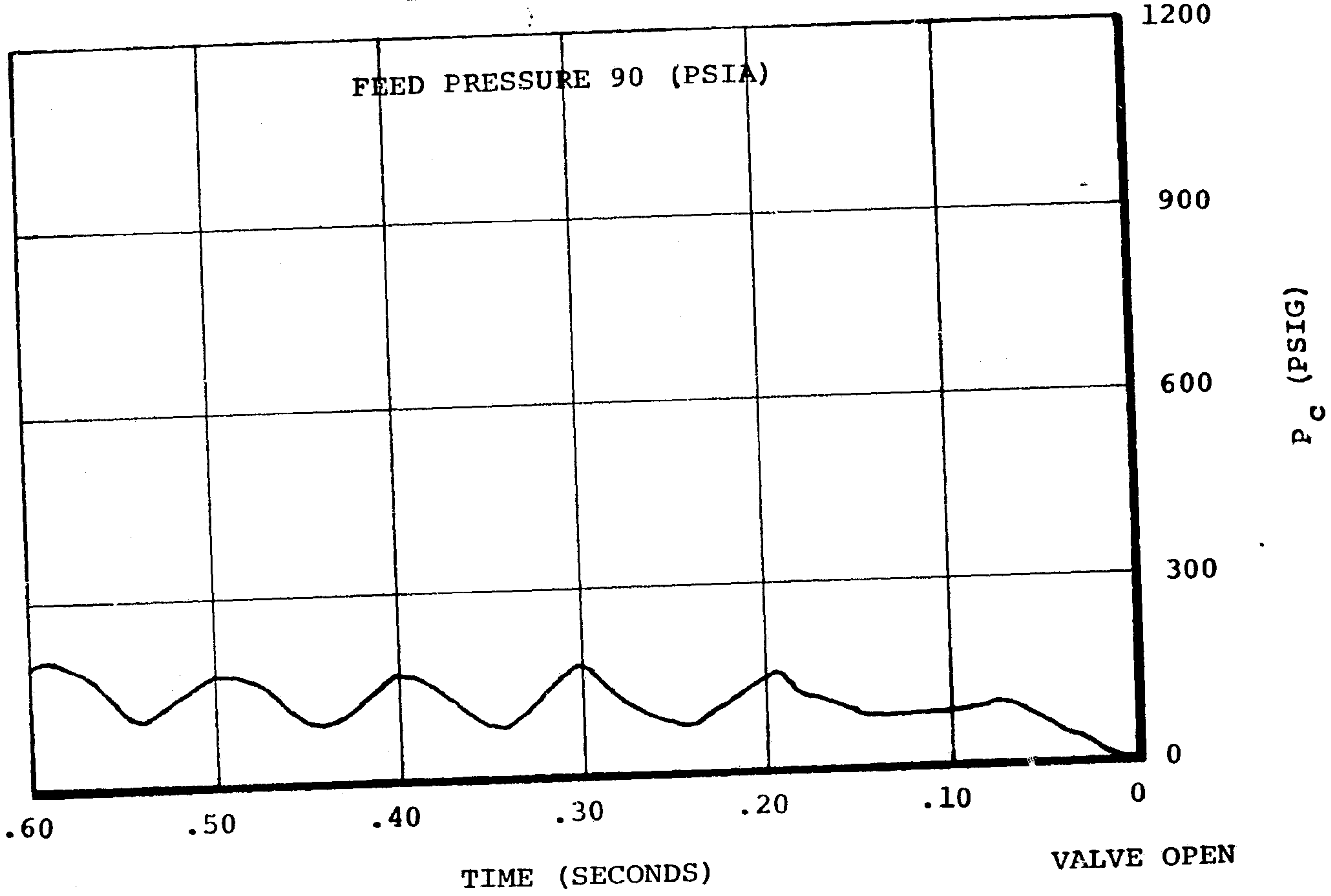


FIGURE 22

2.2 S/N D204 (continued)

The two-minute soakback represented the worst-case thermal condition (ref. Figures 23 and 24), in terms of the temperatures in the injector branch area. Two thermocouples, T_7 and T_8 were mounted on the side wall and base of the injector well (see Figure 25). The thermocouple closes to the branch tubes, T_8, peaked in 120 to 150 seconds.

Figure 26 compares the time to reach a given temperature at T_8 in the test, during soakback, versus that indicated by the model for vacuum conditions in the APU.

In addition to soakback temperatures, Figures 23 and 24 also show temperature transients during the initial 10 seconds of restart. T_8, which was closest to the branch tubes, shows a rapid drop caused by the fuel flow cooling the branch area.

The last five restarts made on D204 before re-pack were all at 80 psi fuel inlet pressure and short soakback time (Run 20 soak was 7 seconds). There were no overshoots (Figures 27 through 31)on any of these runs, but considerable oscillations were again evident. The low pressure starts showed a continued and expected trend toward strong feed system coupling. Flow stagnation and some reverse flow was apparent on some starts, (Figures 32, 33 and 34), but this did not result in any disturbing chamber pressure transients. It was again noted that the engine appeared to rapidly increase in roughness from the previous series, though response and tailoff times were neither in violation of acceptance crtieria, nor as long as seen on other engines exhibiting similar roughness.

The third ATP of D204 showed considerable roughness and an increase in gas temperature. (See Table XI). Both of these phenomena are normally indicative of voiding in the catalyst bed. Tailoff time was up slightly from ATP-2.

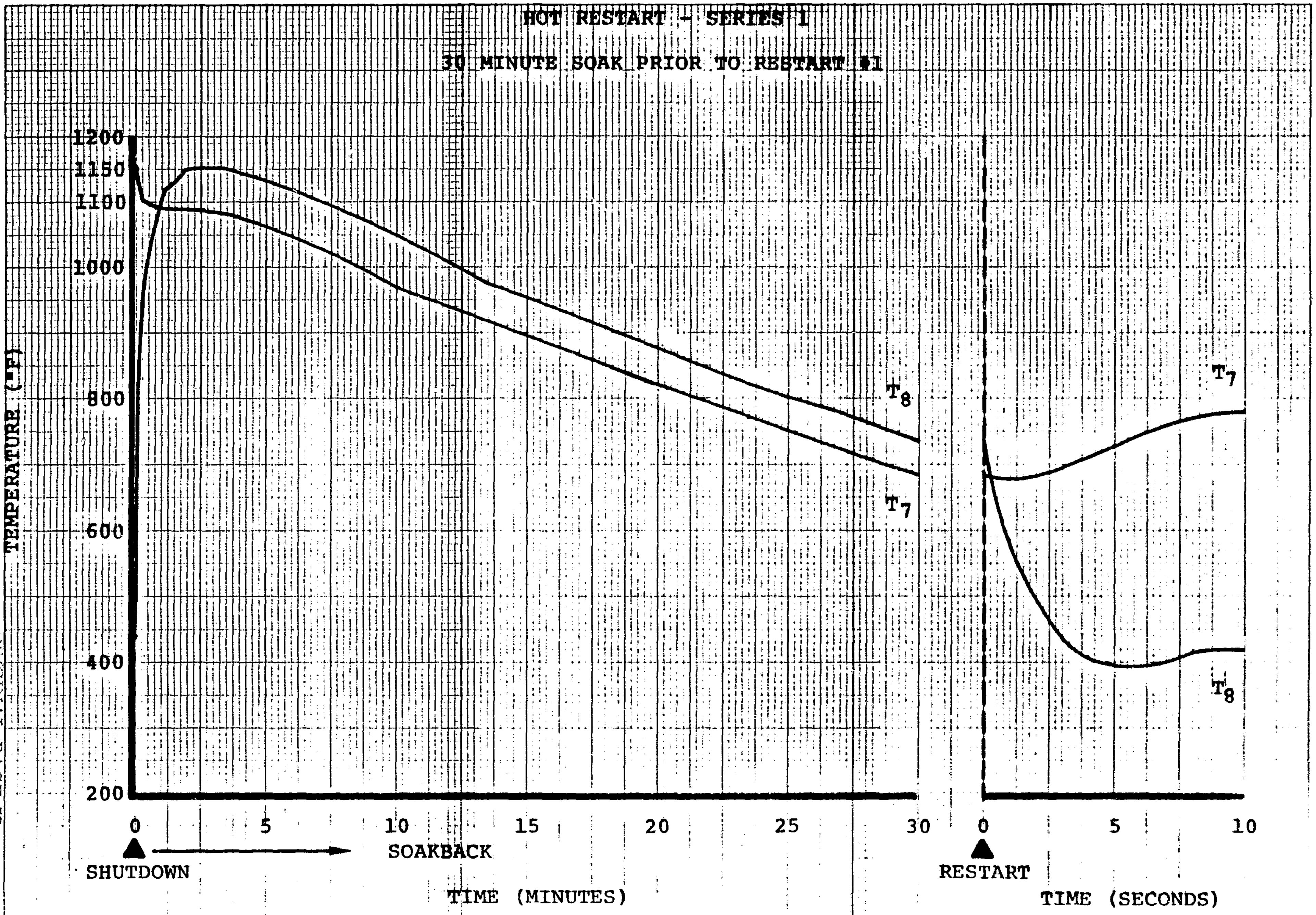

HOT RESTART - SERIES 1
30 MINUTE SOAK PRIOR TO RESTART #1
TEMPERATURE (°F)
1200
1150
1100
1000
800
600
400
200
T8
T7
0
5
10
15
20
25
30
SHUTDOWN
SOAKBACK
TIME (MINUTES)
RESTART
TIME (SECONDS)

FIGURE 23

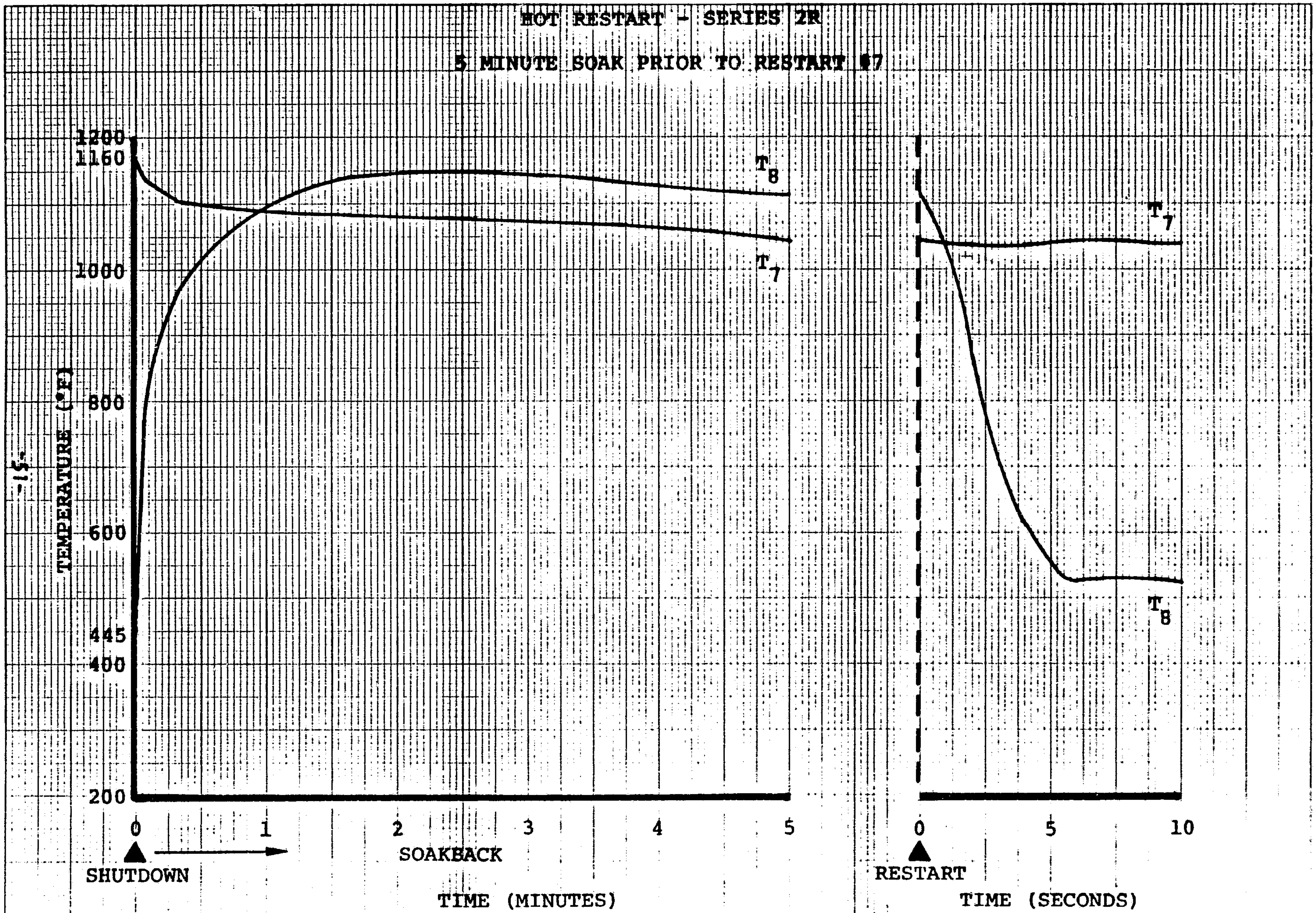
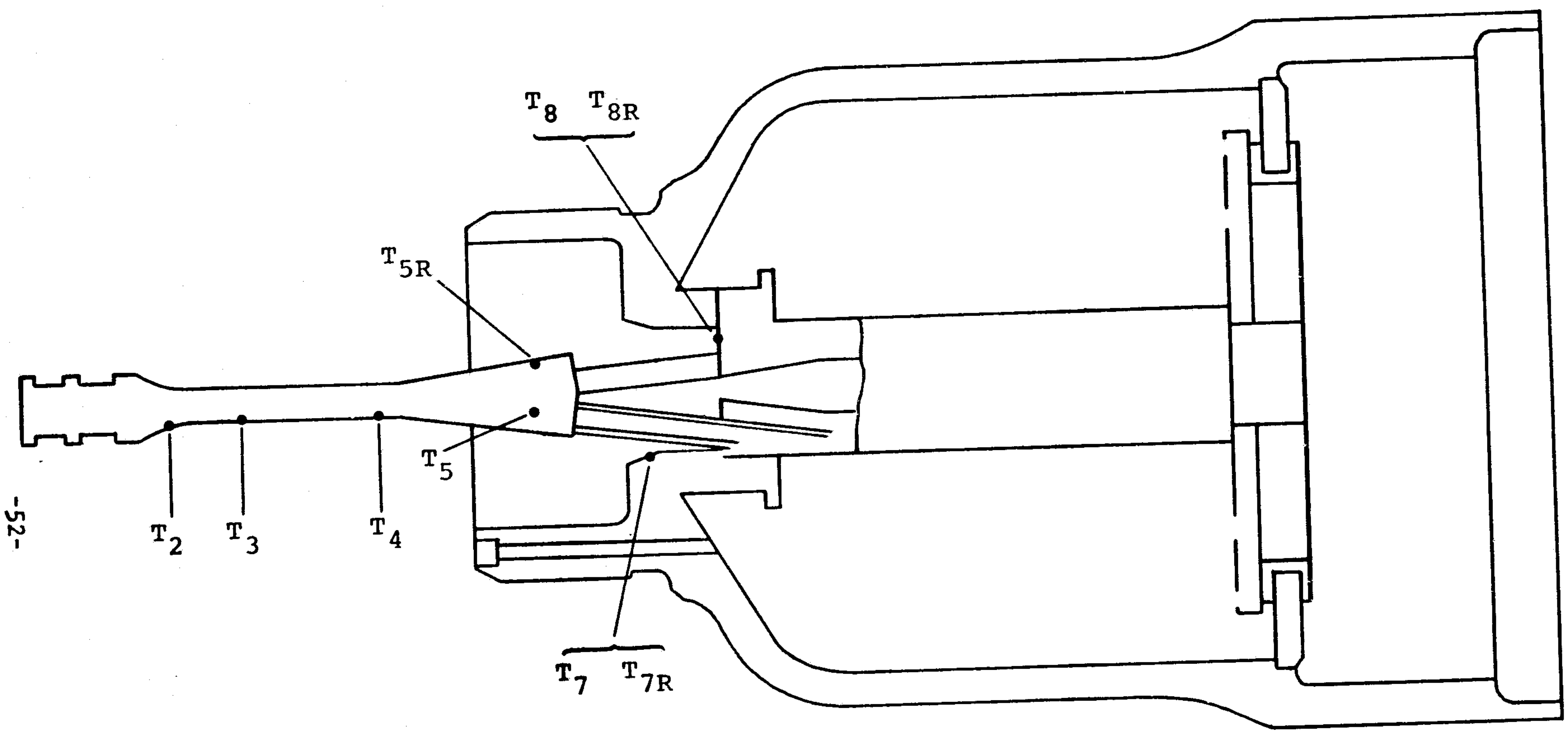

HOT RESTART - SERIES 2R
5 MINUTE SOAK PRIOR TO RESTART #7
TEMPERATURE (°F)
1200
1160
1000
800
600
445
400
200
T_8
T_7
T_7
T_8
0
1
2
3
4
5
0
5
10
SHUTDOWN
SOAKBACK
TIME (MINUTES)
RESTART
TIME (SECONDS)

FIGURE 24



T_P (NOT SHOWN) VALVE MOUNT PLATE

FIGURF 25

SPACE SHUTTLE APU GAS GENERATOR

HOT RESTART TESTS

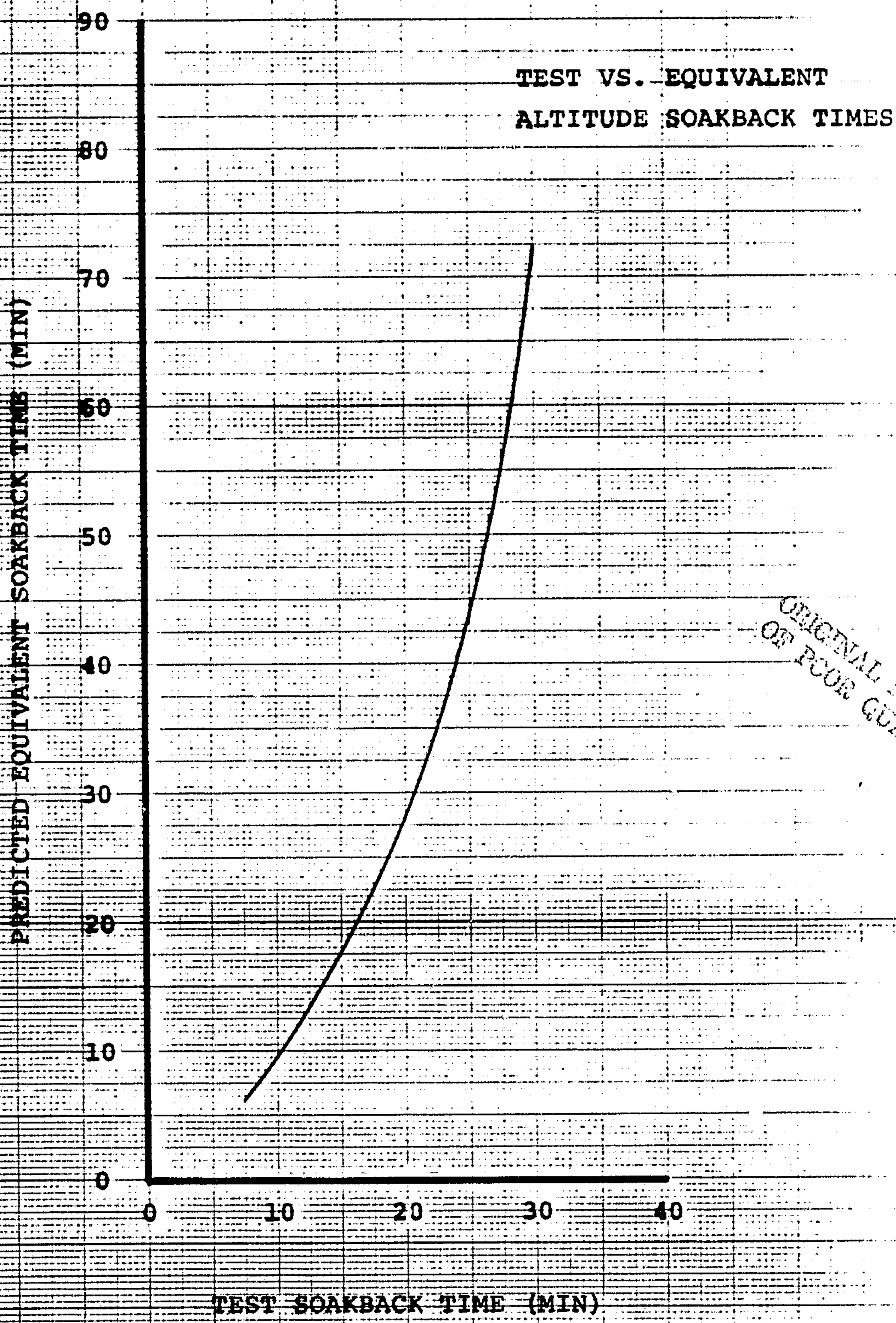


FIGURE 26

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 3
S/N D204 RUN 16
BOOTSTRAP STARTUP

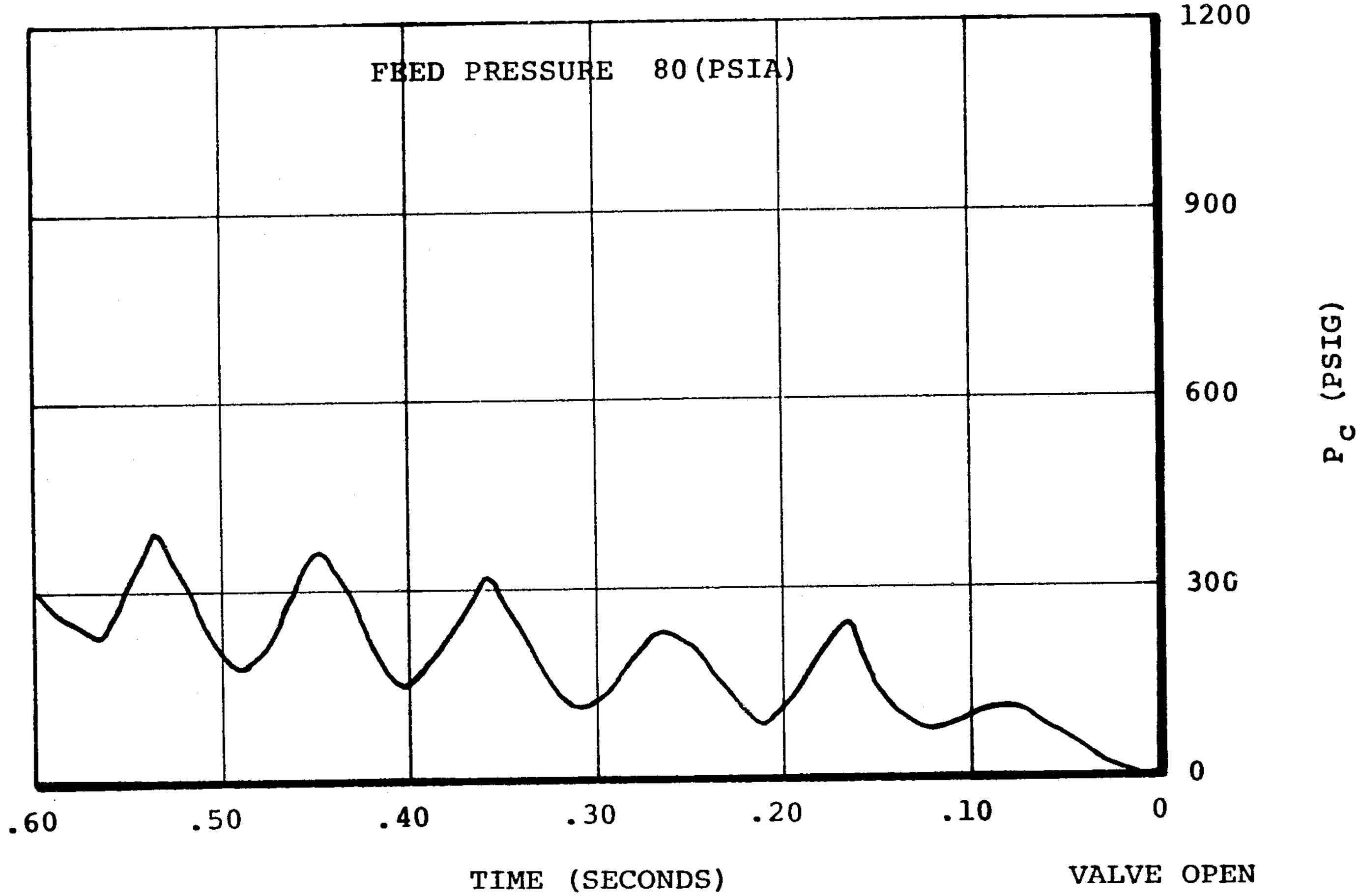


FIGURE 27

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 3
S/N D204 RUN 17
BOOTSTRAP STARTUP

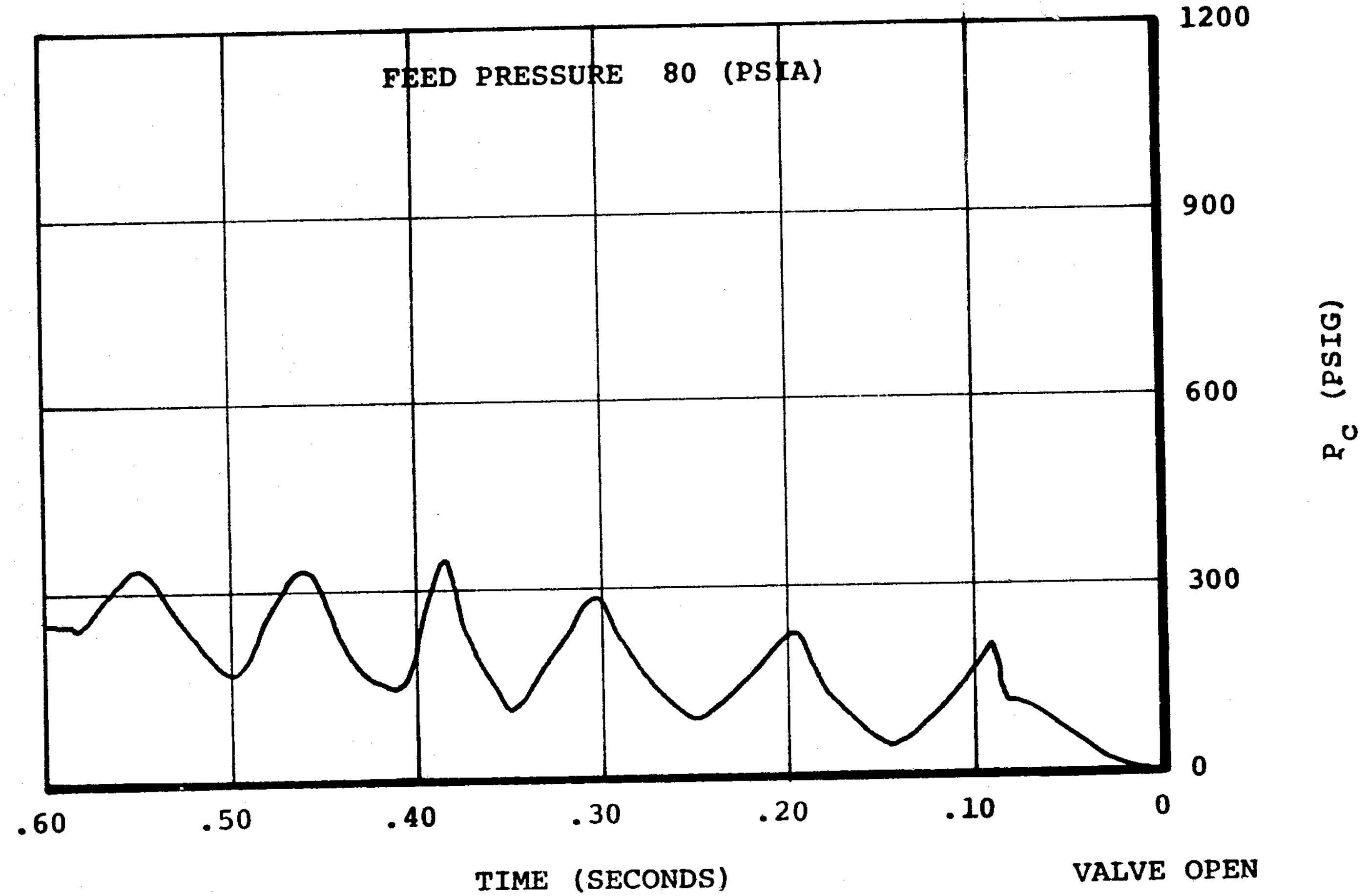


FIGURE 28

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 3
S/N D204 RUN 18
BOOTSTRAP STARTUP

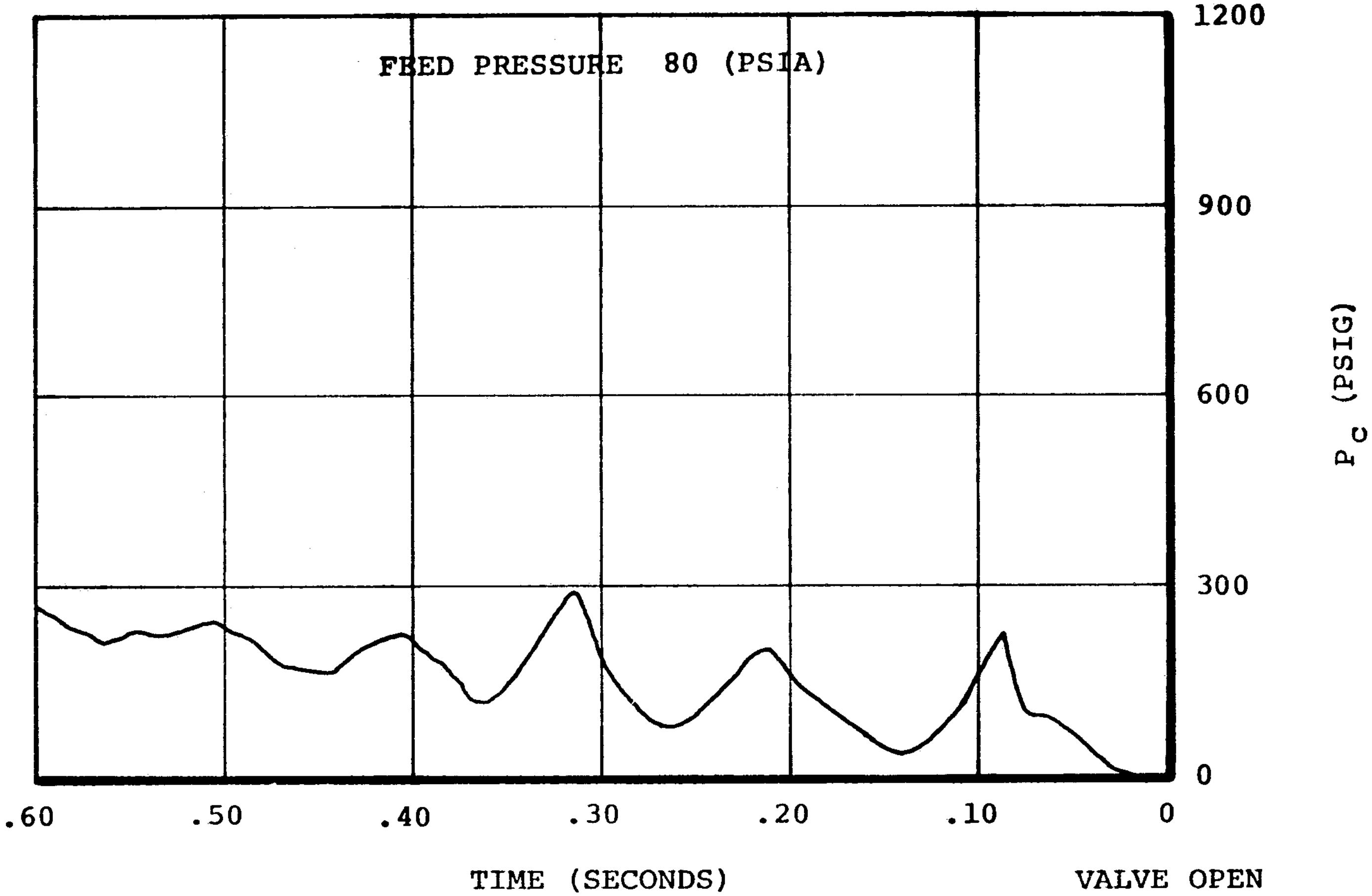


FIGURE 29

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 3
S/N D204 RUN 19
BOOTSTRAP STARTUP

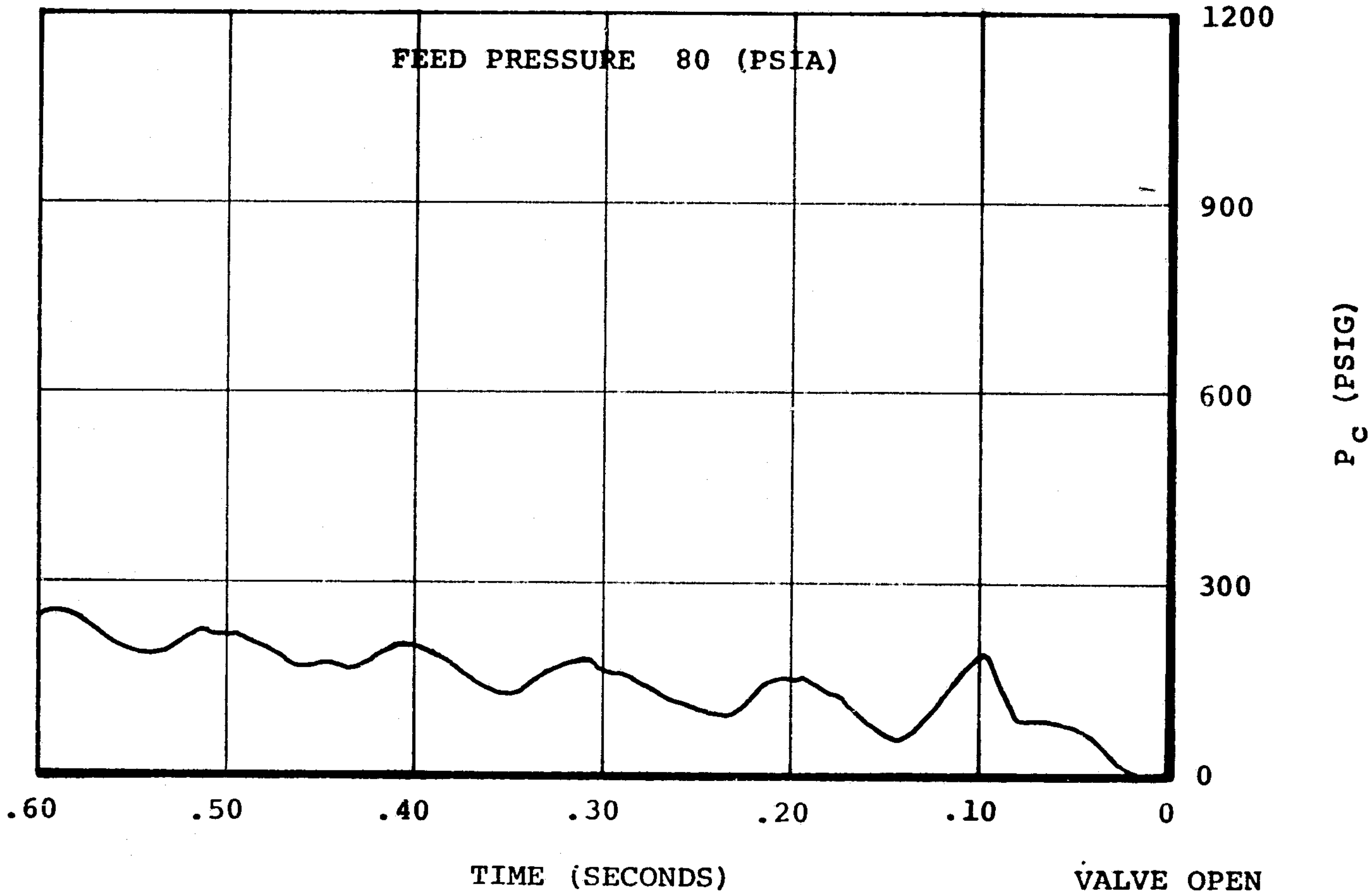


FIGURE 30

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 3
S/N D204 RUN 20
BOOTSTRAP STARTUP

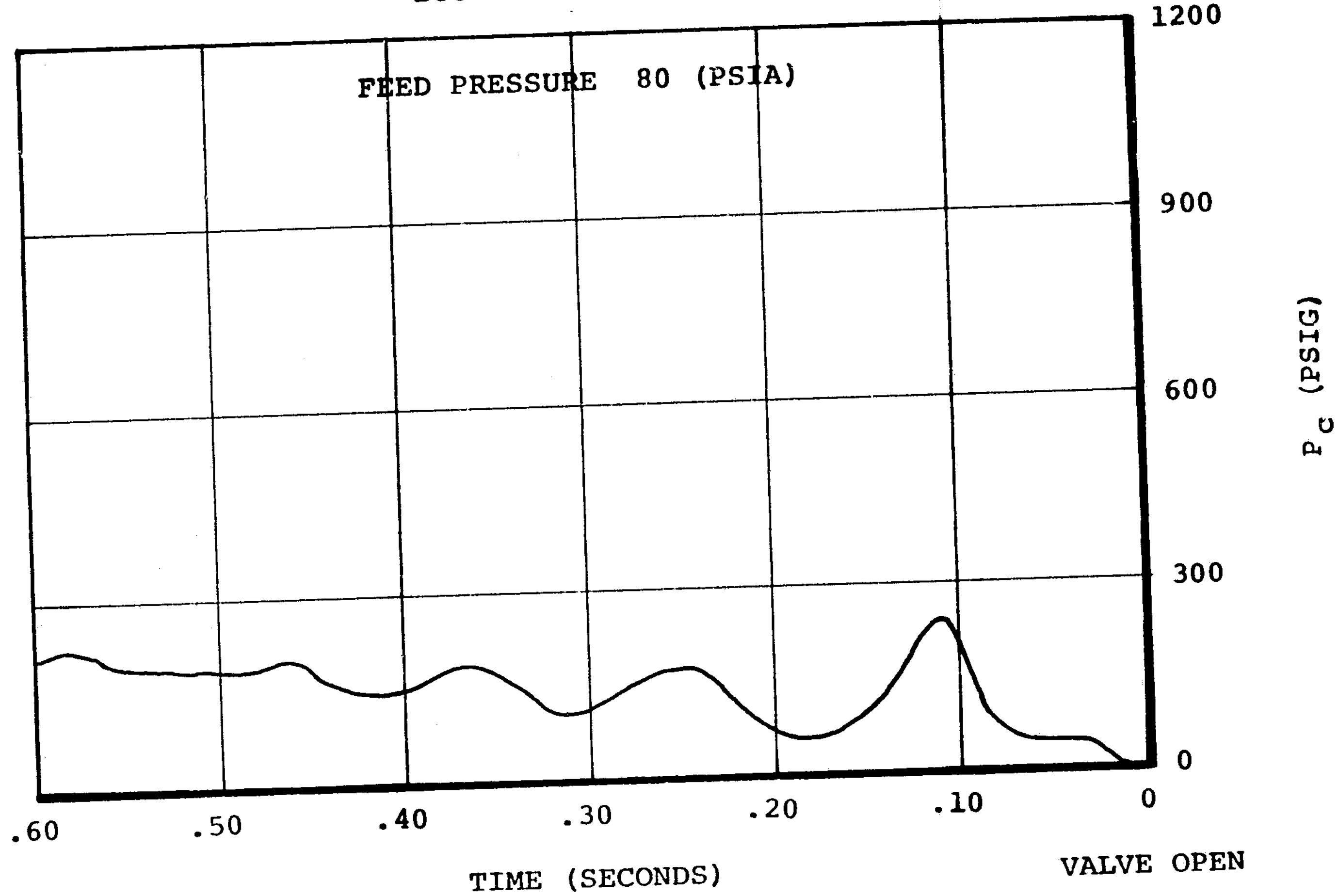


FIGURE 31

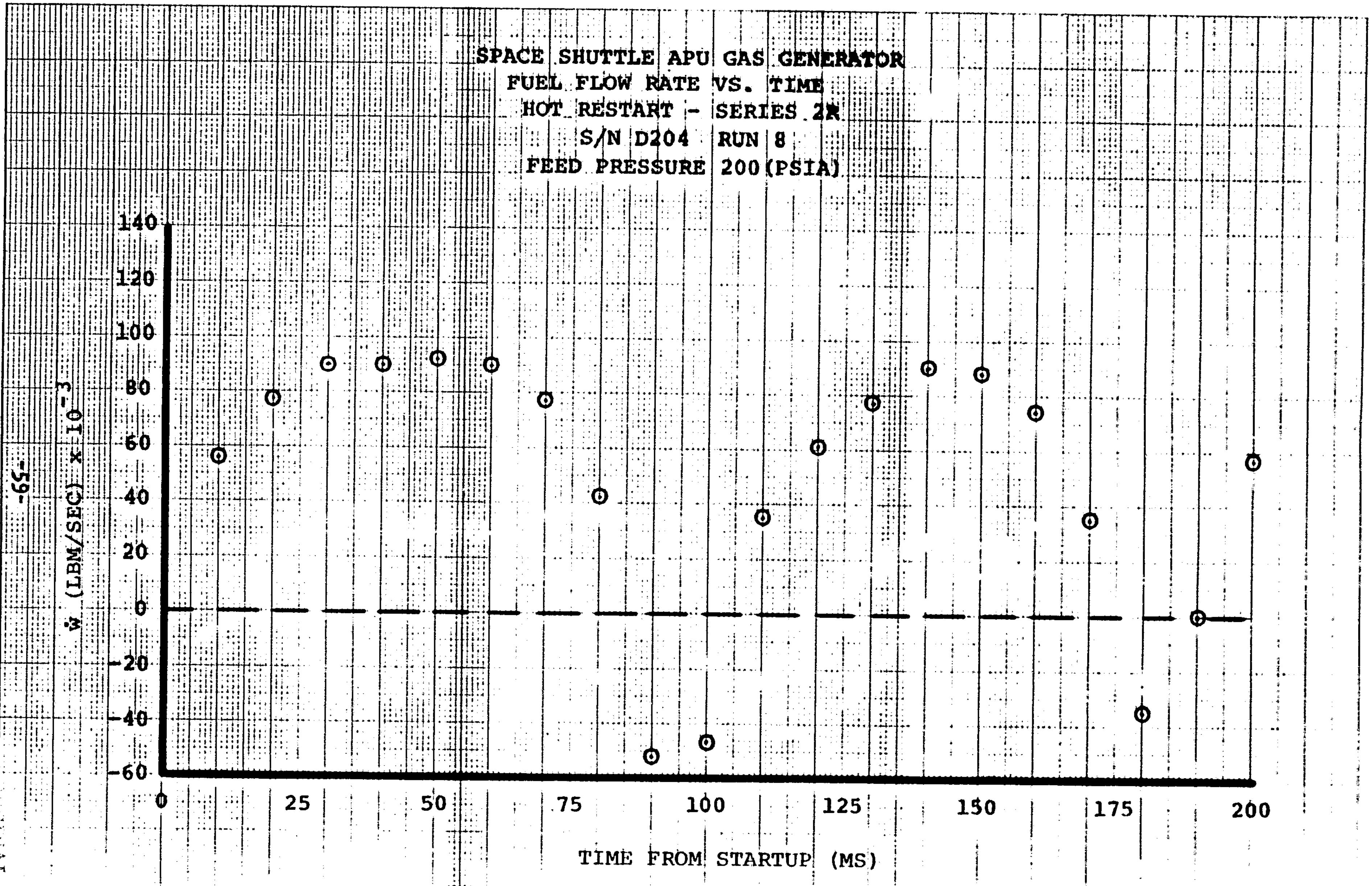

SPACE SHUTTLE APU GAS GENERATOR
FUEL FLOW RATE VS. TIME
HOT RESTART - SERIES 2R
S/N D204 RUN 8
FEED PRESSURE 200 (PSIA)
140
120
100
80
60
40
20
0
-20
-40
-60
$\dot{w}$ (LBM/SEC) x 10^{-3}
0
25
50
75
100
125
150
175
200
TIME FROM STARTUP (MS)

FIGURE 32

SPACE SHUTTLE APU GAS GENERATOR
FUEL FLOW RATE VS. TIME
HOT RESTART - SERIES 2R
S/N D204 RUN 11
FEED PRESSURE 200 (PSIA)

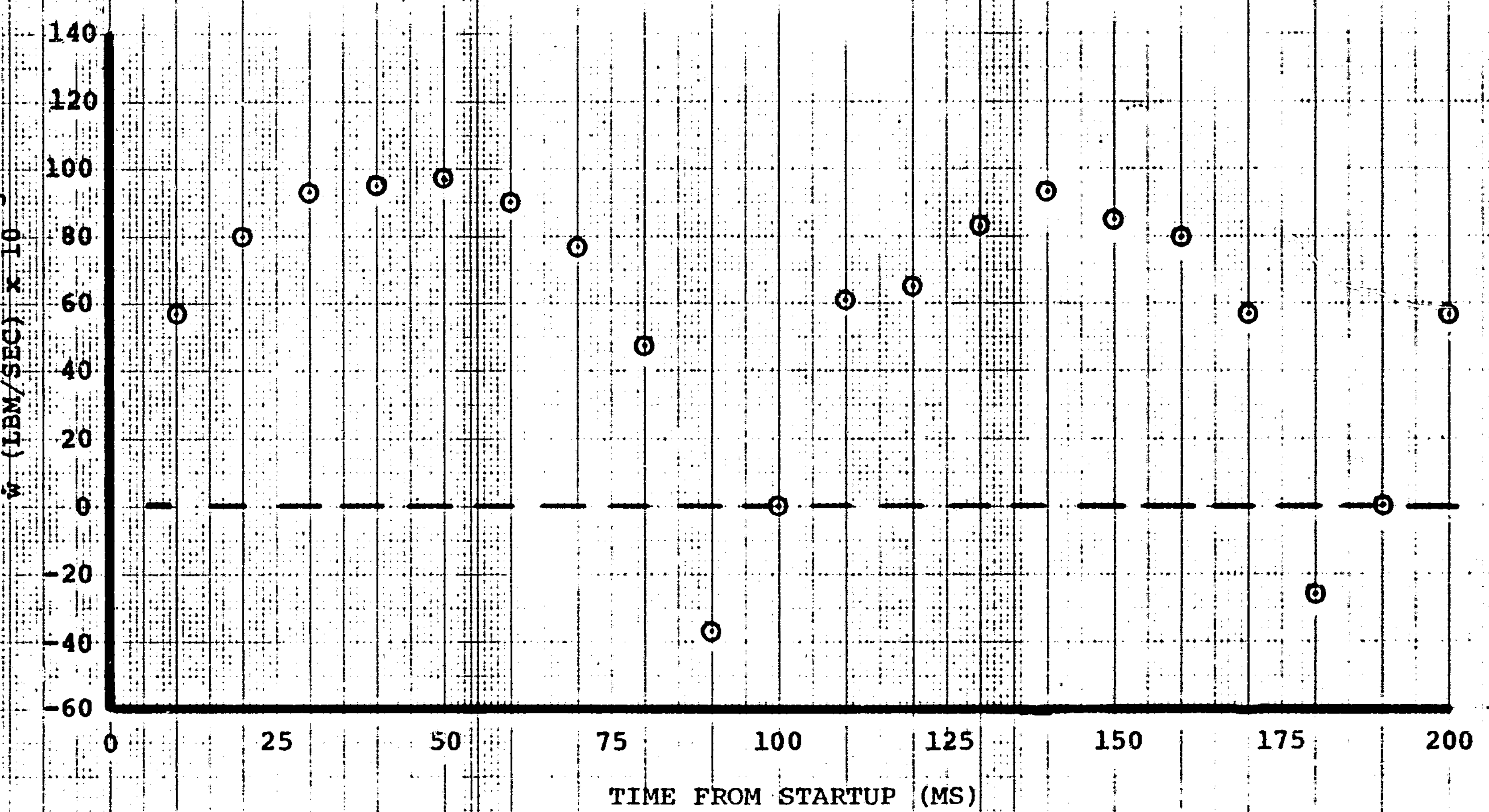


FIGURE 33

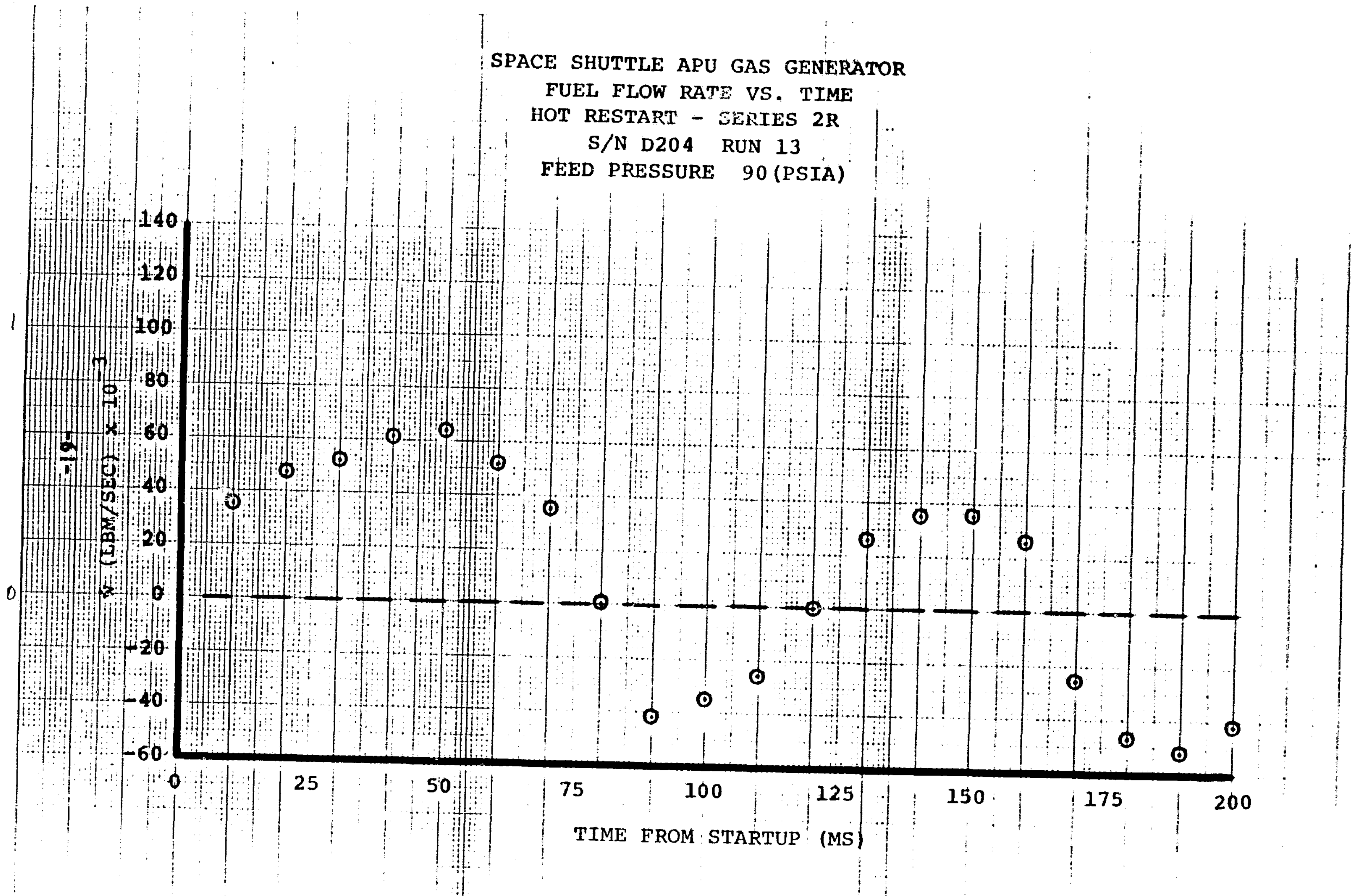

SPACE SHUTTLE APU GAS GENERATOR
FUEL FLOW RATE VS. TIME
HOT RESTART - SERIES 2R
S/N D204 RUN 13
FEED PRESSURE 90 (PSIA)
140
120
100
80
60
40
20
0
-20
-40
-60
ẇ (LBM/SEC) x 10^-3
0
25
50
75
100
125
150
175
200
TIME FROM STARTUP (MS)

FIGURE 34

2.2 S/N D204 (continued)

An examination of the pulse shapes on ATP-3 (Figure 35) showed a marked deterioration in the operation of the unit from that shown during ATP-2.

Review of ATP-3 and hot restart data resulted in a decision to X-ray the unit before any additional testing was attempted. The X-rays showed no apparent voiding in either the inner or outer catalyst beds. The X-ray did indicate severe shortening of the inner bed cylinder, such that it no longer engaged the downstream end closure.

(Unit D205 was also X-rayed at this time to assure the acceptability of bed cylinder engagement in the dowstream end closure. No anomalies were observed on D205).

After firing MDC #4, it was decided to disassemble the unit, examine the bed plate, and re-pack the unit as no improvement was seen in performance, and the inner bed cylinder was certainly not acceptable.

The disassembly showed that the inner bed cylinder was actually compressed approximately 0.170 inches. The slots in the cylinder were closed (Figure 36). This is consistent with the pronounced increase in pressure budget (ref. Table XI) of approximately 14% between ATP-1 and ATP-3. Such bed cylinder compression results in an increased pressure drop through the bed. The inner bed was removed, in axial increments, and although some softness was detected while probing the bed in front of the Rigimesh panels, no voids were noted and the foam was in good condition. A weight gain in the inner bed of ~ 5% was noted and was undoubtedly caused by physical adsorption of water. The compression of the bed cylinder was much greater than could have been caused by assembly error alone. It is possible, however, that the tooling used during packing could have resulted in some initial compression. The foam and catalyst pack would then restrain the bed cylinder and prevent relaxation/elongation after removal of the tooling. If the inner

SPACE SHUTTLE APU GAS GENERATOR
TYPICAL PULSES
ATP-3
S/N D204 (ICGG)

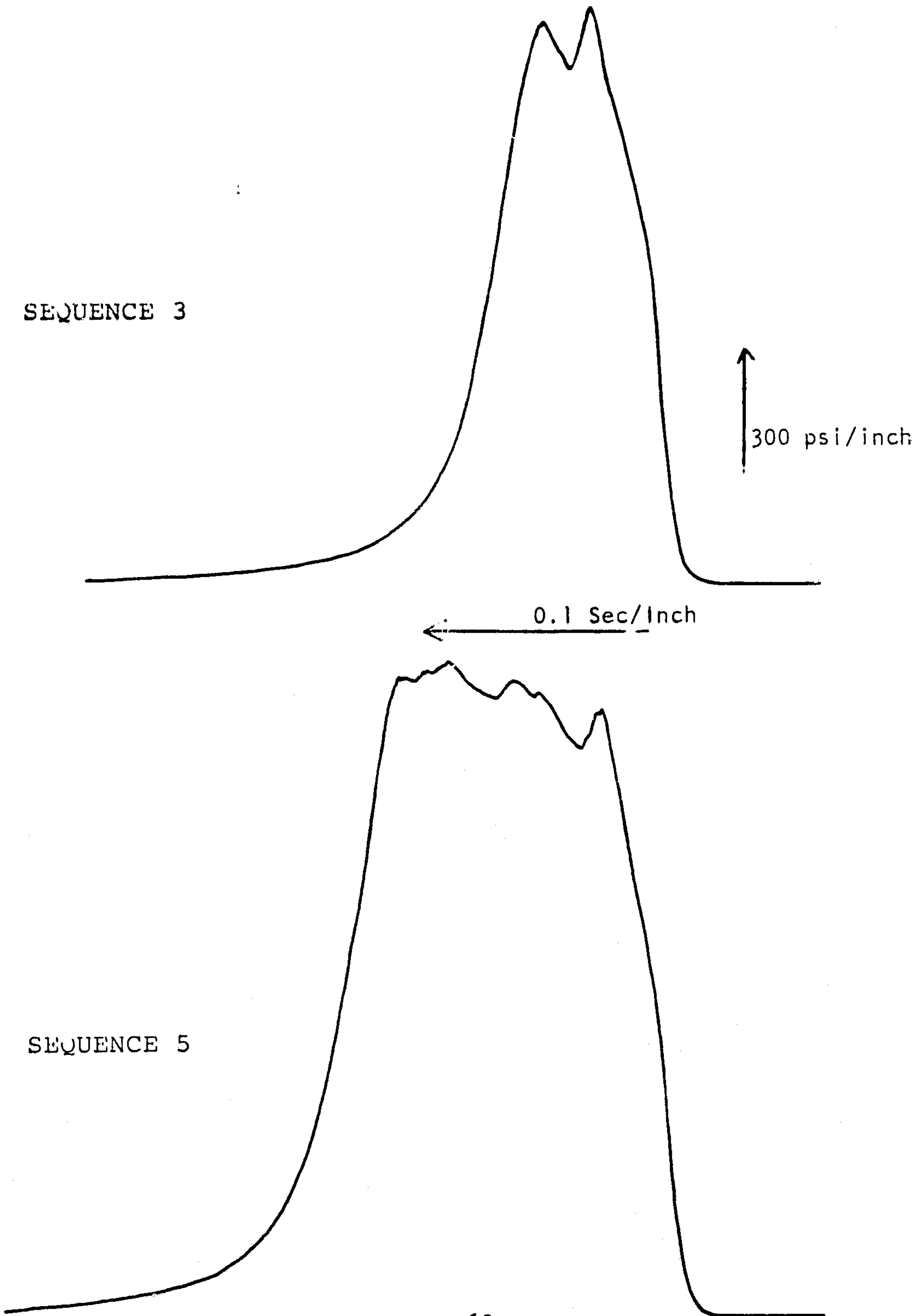
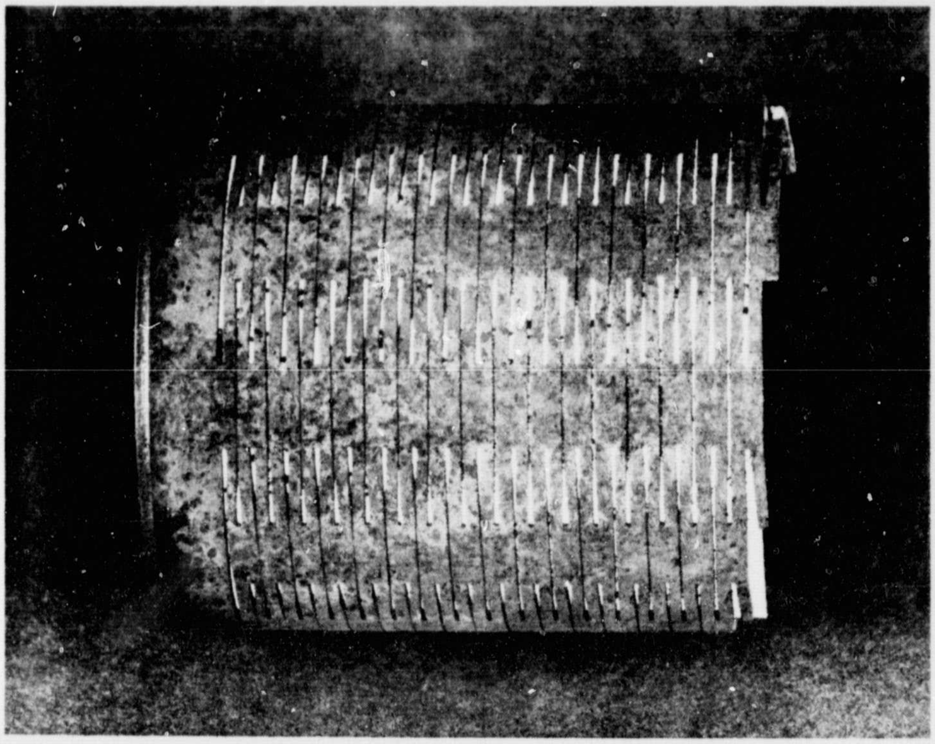


FIGURE 35

D204 INNER BED CYLINDER



2.2 S/N D204 (continued)

bed cylinder did not seat in the downstream bed closure, the slot would have become filled with catalyst particles. Subsequent thermal cycles, during firing and coolir , could have resulted in differential expansion of the injector and bed cylinder which would alternately compress the cylinder against the catalyst particles or contract the bed cylinder, allowing loose catalyst to fill the space, setting the cylinder up for additional compression. (See Figure 37).

2.3 S/N D204A

After D&I of the D204 bed, the unit was repacked with new catalyst, foam, and inner bed cylinder. Engineering inspection by Program Office of the final pack showed that the inner bed cylinder had adequate engagement in the end closure. The catalyst packs and foam weights for D204, D204A, and D205 are recorded in Table XIV for reference.

After Proof and Leak checks were performed, an initial ATP was run on D204A. The data showed a smooth running generator with somewhat higher gas temperature than the initial build of D204. The roughness was lower than ATP-1 on D204, (40% for average roughness on Sequence 4 though the same average roughness on Sequence 7), and an examination of the pulse shapes (Figure 38) showed them to be smoother (more nearly resembling S/N 3007 pulses, Figure 9).

This design has a lower injection momentum than the Minor Modification design and higher roughness and a fair amount of scatter in roughness is to be expected.

A series of five hot restarts were run on S/N D204A to compare with selected data from S/N D204. Conditions run (ref. Table IX) were chosen to repeat some of the restarts with the most severe overshoots

BED CYLINDER COMPRESSION MODEL

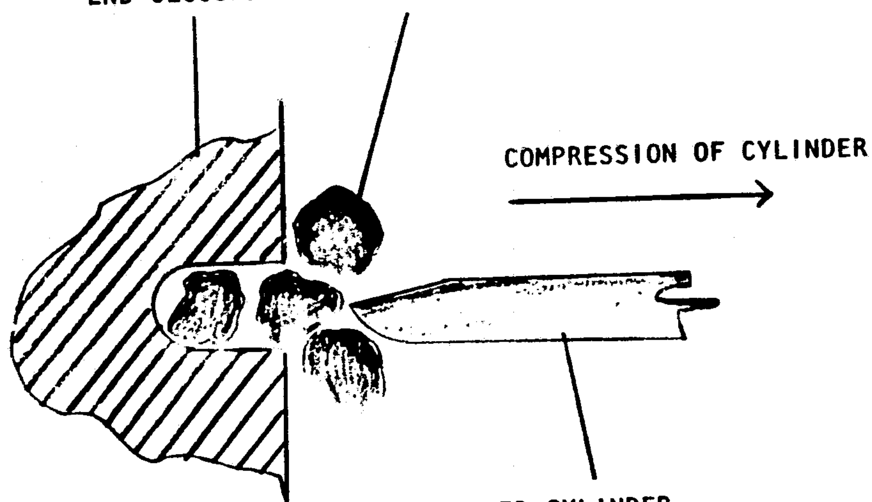


FIGURE 37

TABLE XIV

GAS GENERATOR PACKING DATA

S/N	WEIGHT INNER BED (Grms)	WEIGHT OUTER BED (Grms)	WEIGHT FOAM (Grms)
D204	42.90	71.0	10.51
D204A	41.16	68.11	11.585
D205	40.37	69.40	10.65

SPACE SHUTTLE APU GAS GENERATOR
TYPICAL PULSES
ATP-1
S/N 204A (ICGG)

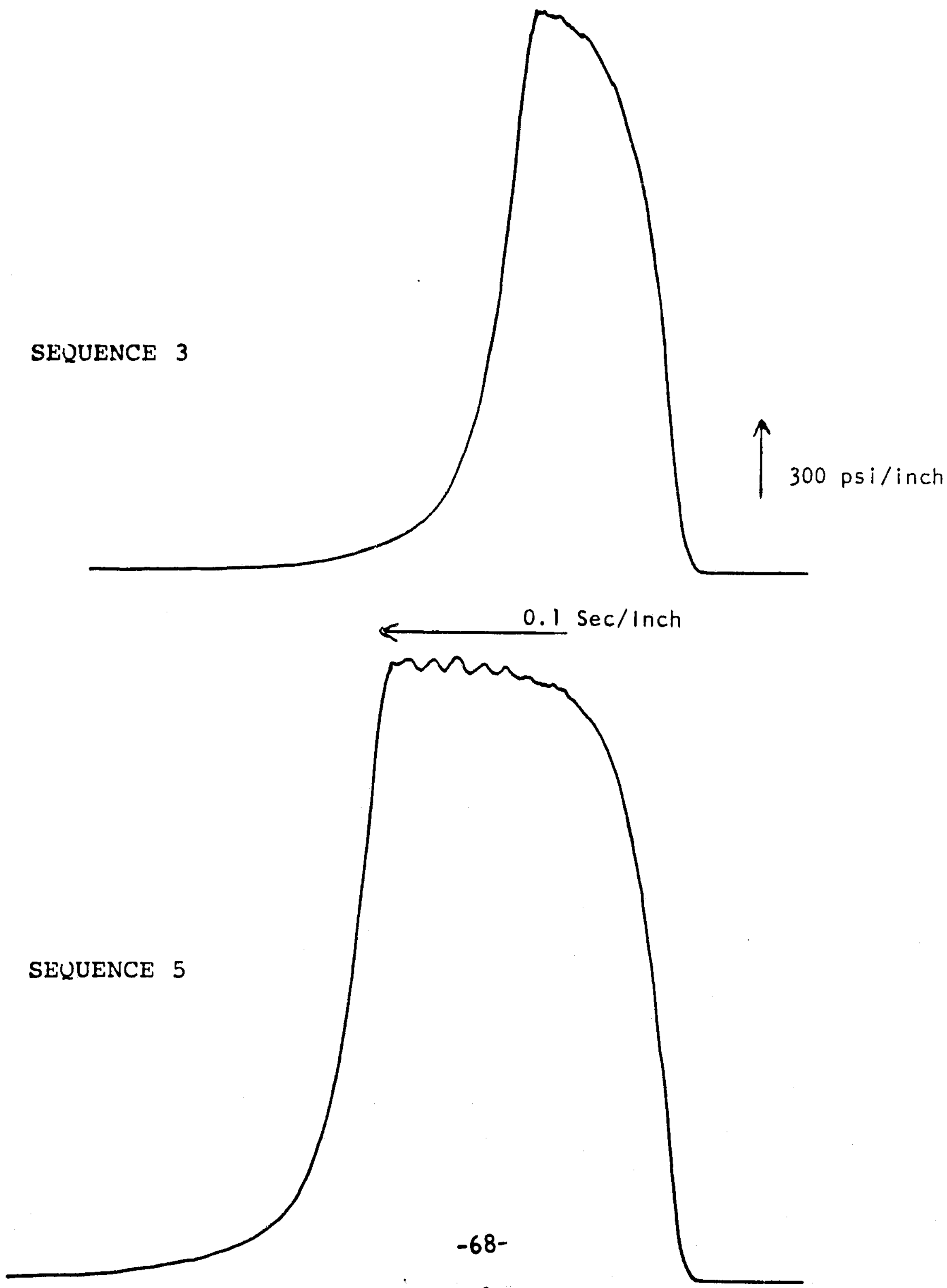


FIGURE 38

2.3 S/N D204A (continued)

and the final run was at the minimum feed pressure (80 psi) with the soakback time of 2 minutes. Only Runs 1 and 3 with 400 psi fuel inlet pressure showed any significant overshoots (Figures 39 and 40), and these overshoots were significantly lower than those seen under the same conditions on S/N D204 (Table XIII).

The runs with overshoots again exhibited surge flowrates somewhat higher than those without overshoots. Run 4, which had a 400 psi feed pressure, had a surge flowrate almost as high as the runs manifesting overshoots. While no overshoot, characterized by a sharp pressure peak, was noted on that start, the initial chamber pressure oscillation (400 psi) was higher than for the lower pressure starts. Chamber pressure oscillations on this run damped out within 30 ms. of start as expected with the higher initial feed pressure. Pulse shapes, particularly during pressure rise, appeared very good.

A reference ATP was run on S/N D204A after hot restart testing to verify acceptability for shipment. The gas temperature, though lower than that for Minor Modification Gas Generators, is within the predicted range for this design. The other parameters were all acceptable and nominal. Roughness was lower than when the bed was new, which tends to indicate some smoothing of the catalyst's spatial distribution with the first few firings. Pulse shapes (Figure 41) were quite smooth.

After decontamination, the unit was X-rayed to verify acceptable seating of the bed cylinders in the end closures. Although the cylinders were not completely bottomed-out, there was adequate engatement to prevent catalyst from getting into the slots, forcing the bed cylinders out and starting the compression process seen on D204. Tolerance stackups allow a condition of as much as 0.009 inches clearance

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 1'
S/N D204A RUN 1
BOOTSTRAP STARTUP

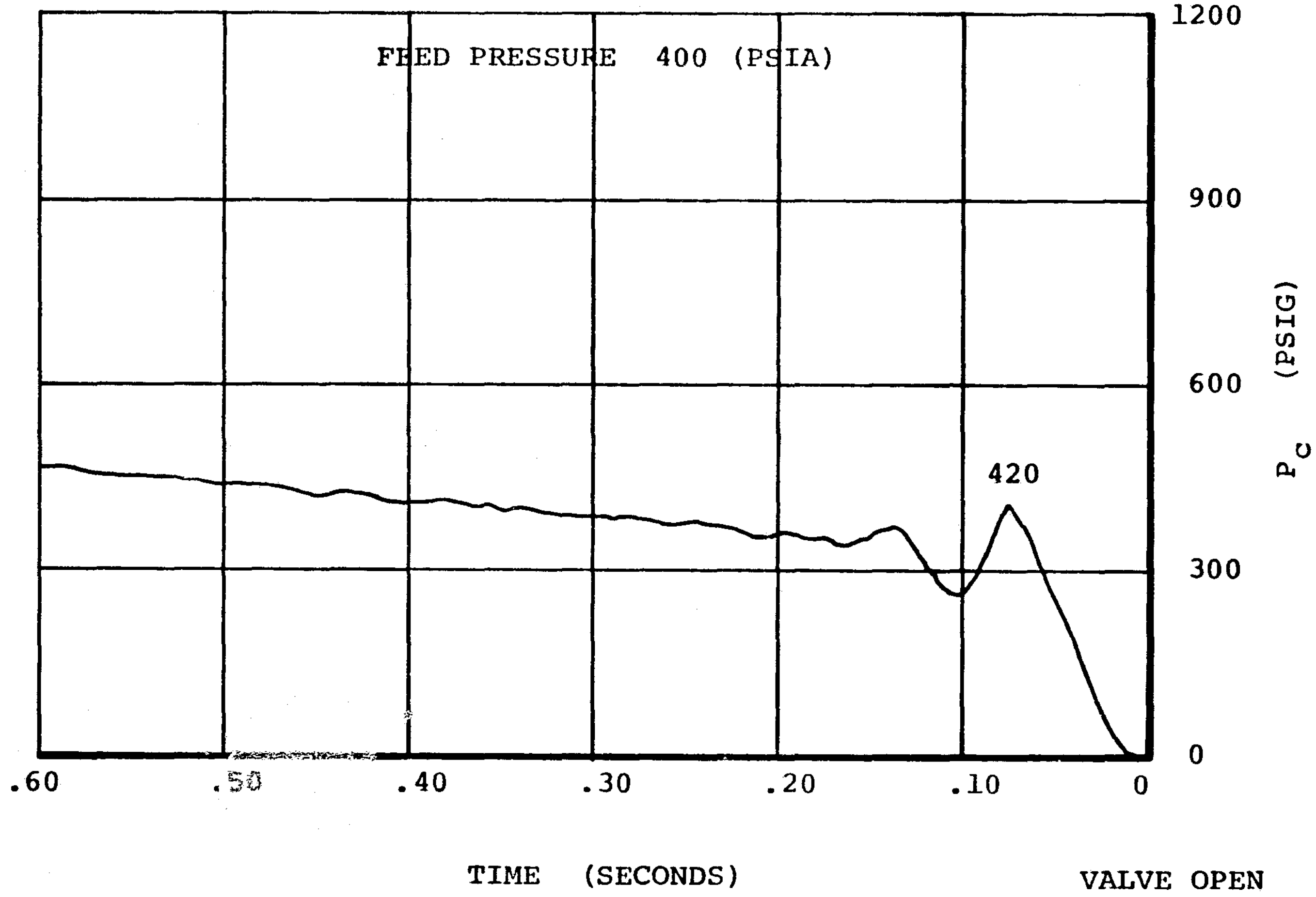


FIGURE 39

SPACE SHUTTLE APU GAS GENERATOR
CHAMBER PRESSURE VS. TIME
HOT RESTART - SERIES 1
S/N D204A RUN 3
BOOTSTRAP STARTUP

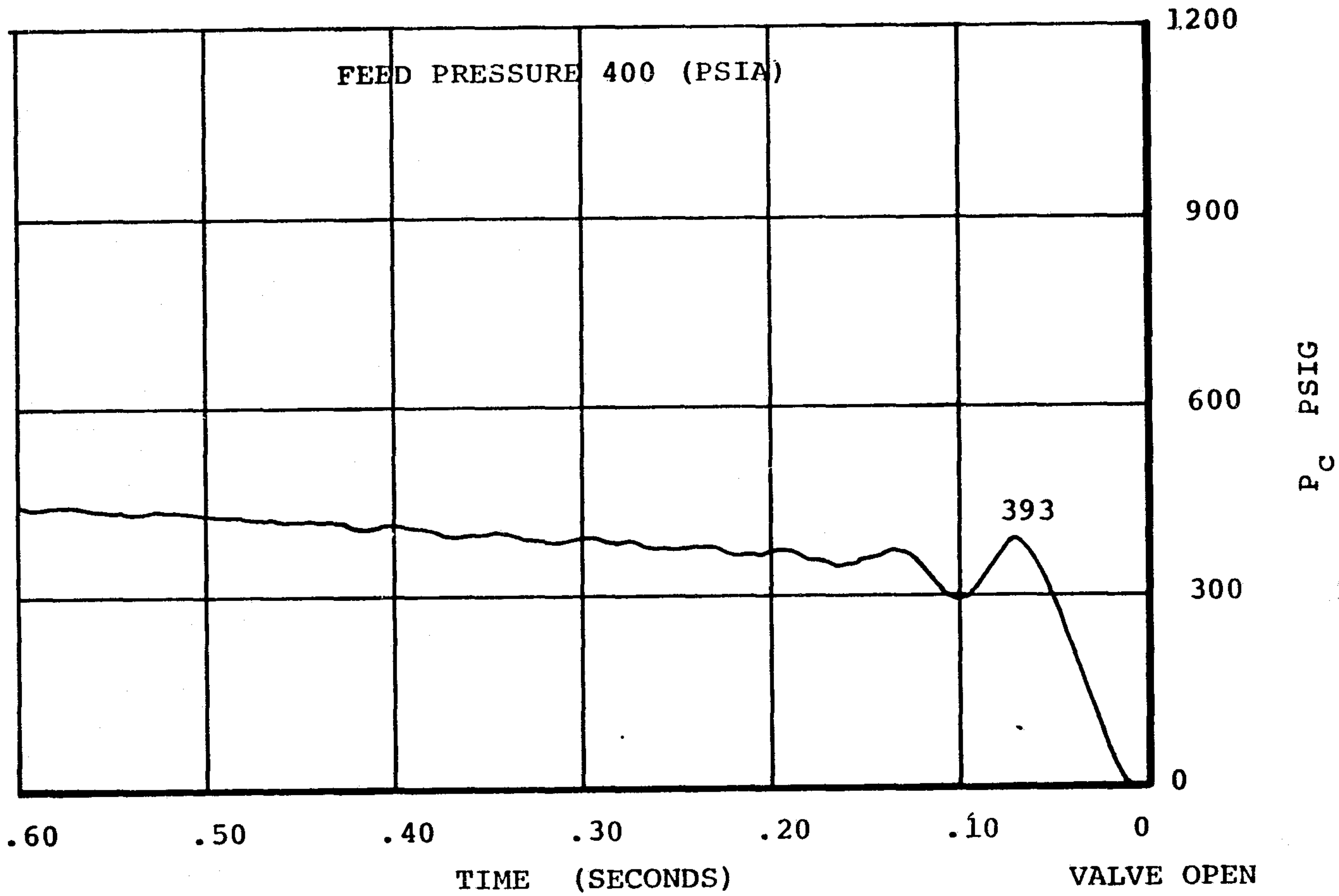


FIGURE 40

SPACE SHUTTLE APU GAS GENERATOR
TYPICAL PULSES
ATP-2
S/N D204A (ICGG)

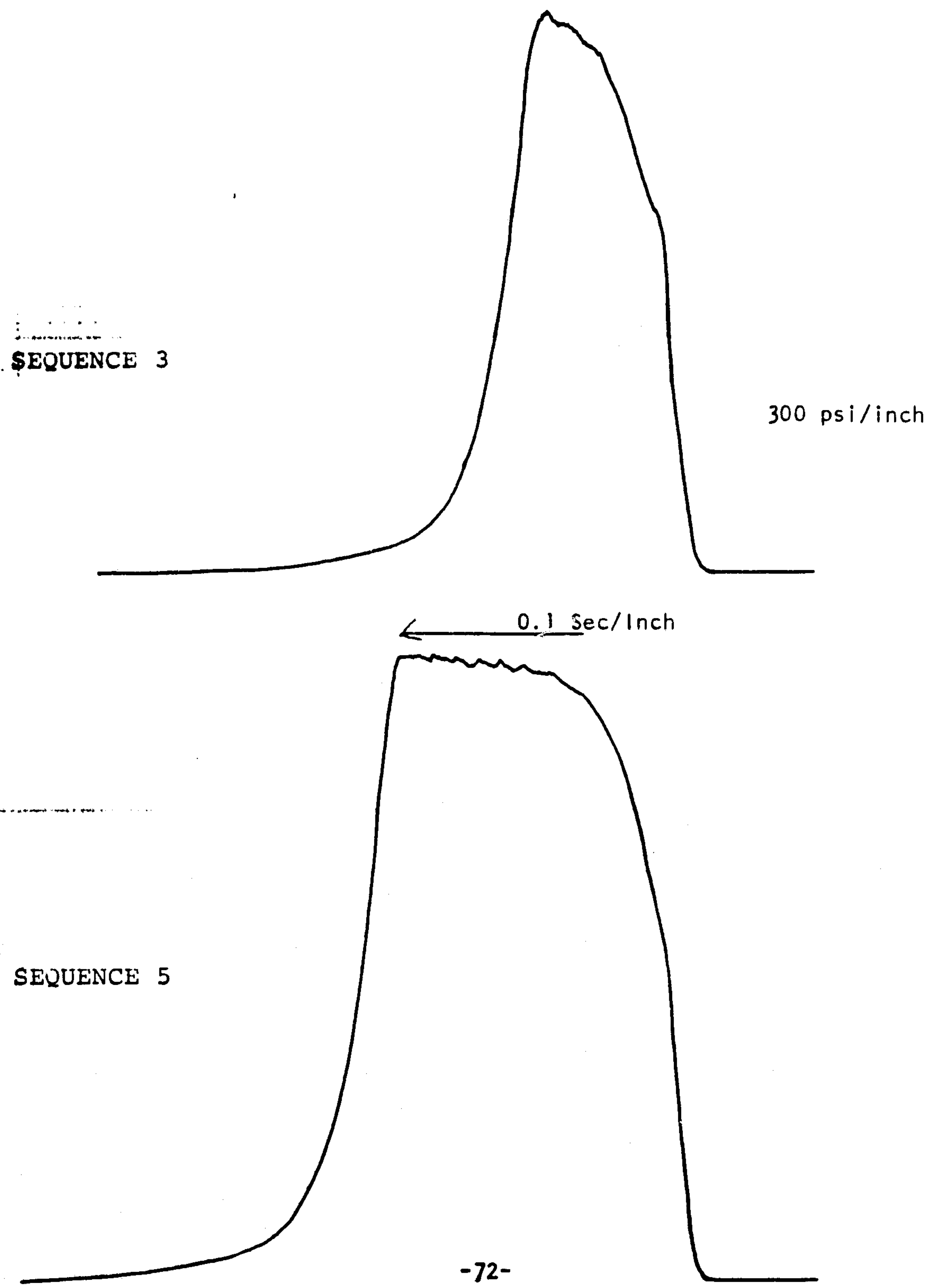


FIGURE 41

2.3 S/N D204A (continued)

at the assembly level. Some additional compression is normal and has been documented on some Space Shuttle Gas Generators (S/N's 1010A/C, D203, 1002AM/C, and others).

After X-ray, final preparation was made and the unit was shipped to JSC.

2.4 S/N D205

The unit received a standard ATP (Appendices "A" through "E"), and an X-ray to assure acceptability. The ATP firing showed somewhat higher maximum roughness than that seen on S/N D204 or S/N D204A, on initial furings (Table XI). All other parameters were in the family. The pulse shapes were rough and resembled those seen on the first firing of S/N D204 (see Figures 42 and 8). Smoothing of the pulse shapes and steady state roughness was noted during early operation on S/N D204 and may be expected here, due to some redistribution of the catalyst bed. Table XIV shows a comparison of bed packing of the three generators. S/N D205 received a slightly lighter pack on the inner bed than the other two units. This may, in part, account for the slightly higher initial roughness. The post-firing X-ray of the bed showed the bed cylinders to be well-seated in the slots of both end closures.

2.5 COMPARISON WITH MINOR MODIFICATION TESTING

2.5.1 Hot Restart

When the performance of the ICGG design hot restarts are compared with that of non-Actively-Cooled Minor Modification

SPACE SHUTTLE APU GAS GENERATOR
TYPICAL PULSES
ATP-1
S/N D205 (ICGG)

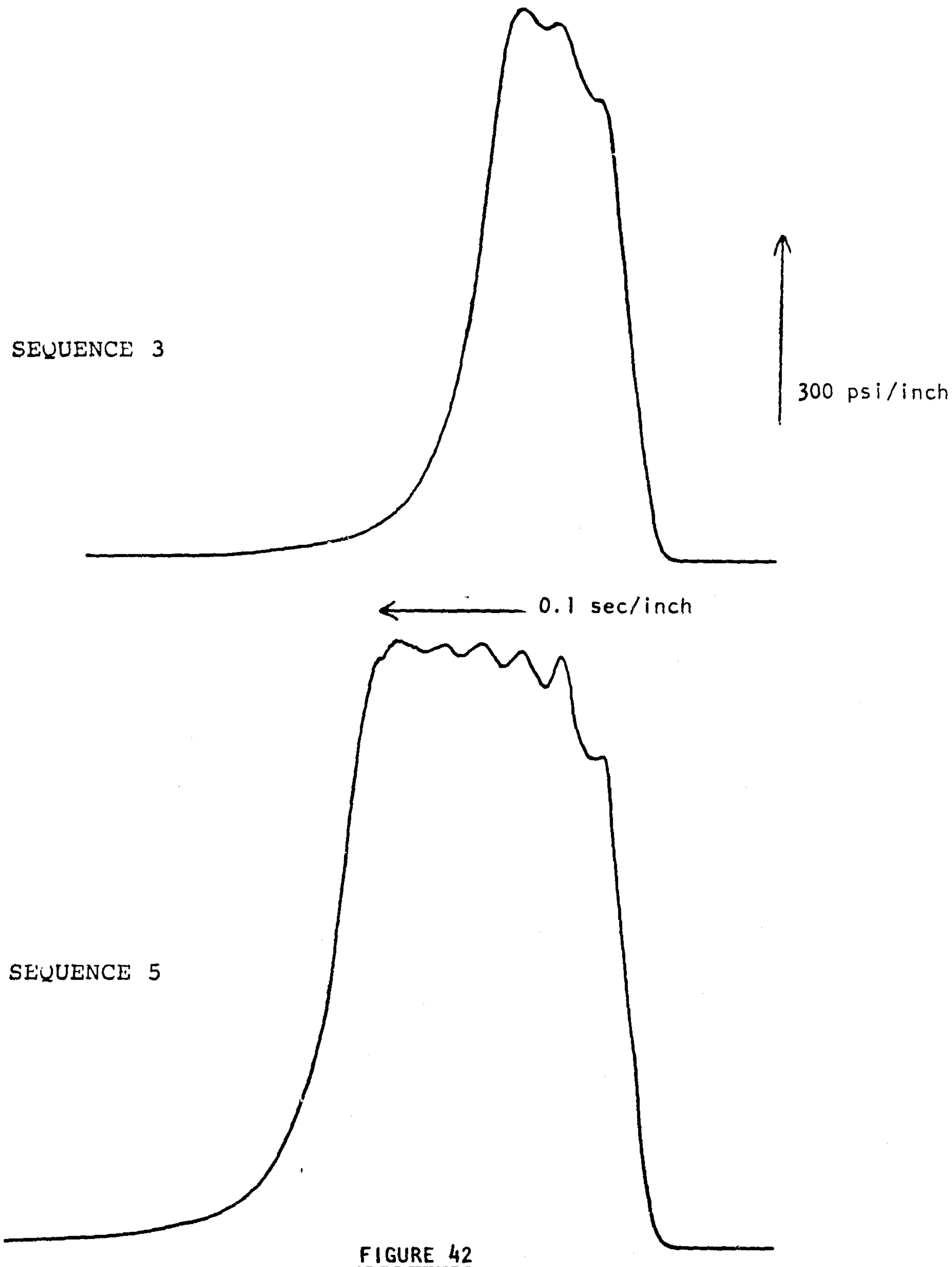


FIGURE 42

2.5 COMPARISON WITH MINOR MODIFICATION TESTING (continued)

2.5.1 Hot Restart (continued)

units, certain differences in system dynamics are noted. On starts where overshoots occurred in the ICGG, the overshoots were always of greater magnitude at the chamber pressure transducer than the feed system pressure transducer. This was often not the case on Minor Modification Unit S/N D03B, where those starts resulting in overshoots often saw more severe response on the fuel pressure transducer. The response at P_f overshoot lagged Pc on the ICGG by 1-2 ms., while it led the Pc overshoot on Minor Modification units by about the same amount. This indicates a fundamental difference in the governing phenomena. In the ICGG, overshoots appeared to be caused by very rapid ignition of an initial slug of fuel in the bed. Damping and delay of the pressure wave from this point to the fuel line caused the lag and reduced magnitude of the fuel system pressure response. The Minor Modification units, on the other hand, appeared to manifest an ignition in the fuel system (probably the gas generator feed stem/branch passage area). Such an ignition, predicted by the negative thermal margin, would result in the higher overshoot pressure at the fuel feed pressure transducer, with chamber pressure lagging by 1-2 ms. Figures 43 and 44 show traces for Pc and P_f on such ICGG and Minor Modification starts. Note that these starts were performed at different initial conditions. The overshoots in the ICGG tests which appear only at high feed pressure are attributable to surge flow.

Ignitions in the branch tubes constitute the "classical hot restart" failure mode. While adiabatic compression detonation of a bubble in the fuel system may be initiated by

D204 HOT RESTART #10

P_f = 400 psi

T_8 @ Restart = 1070°F

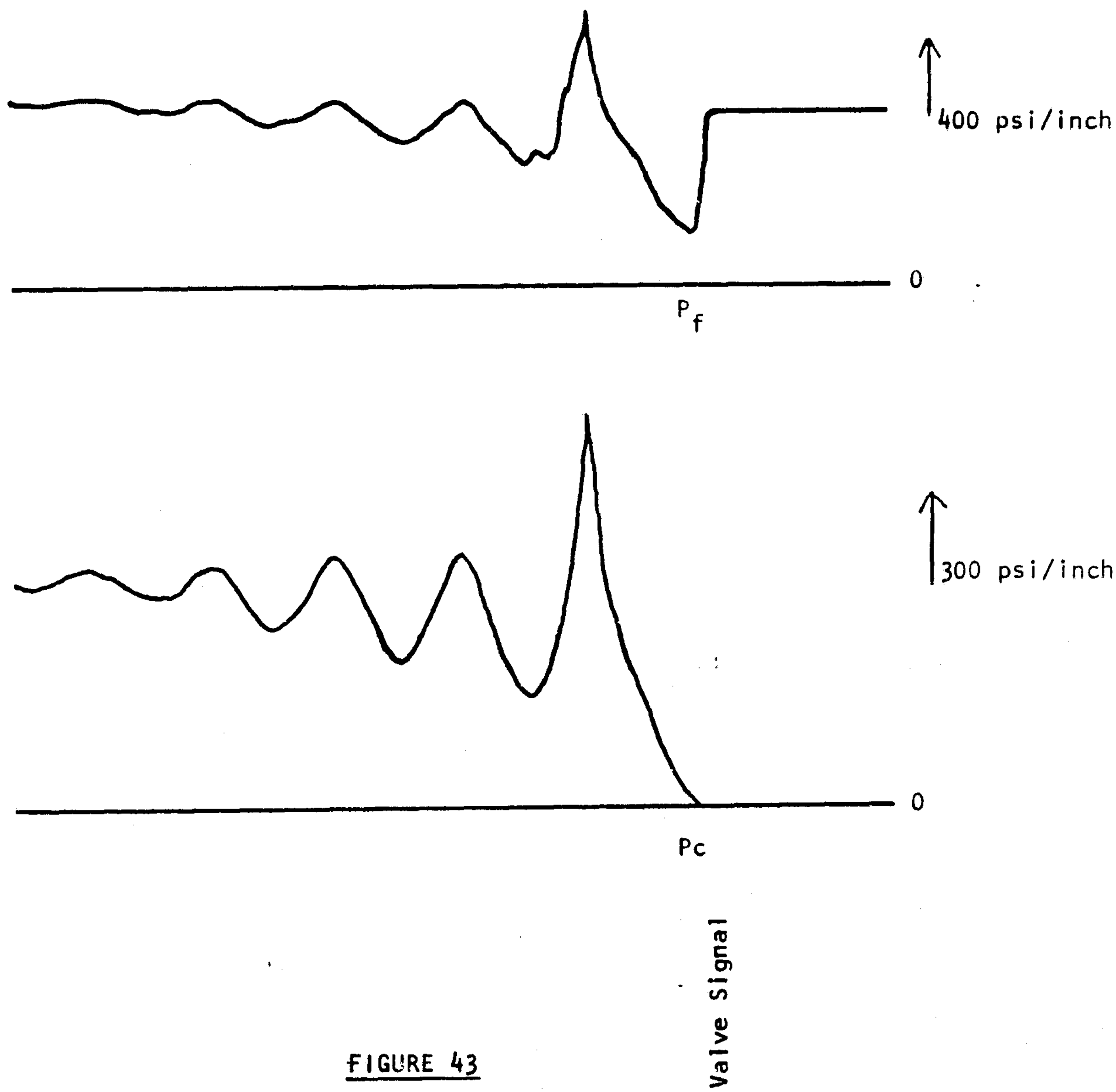


FIGURE 43

D03B HOT RESTART #23

P_f = 160 psi

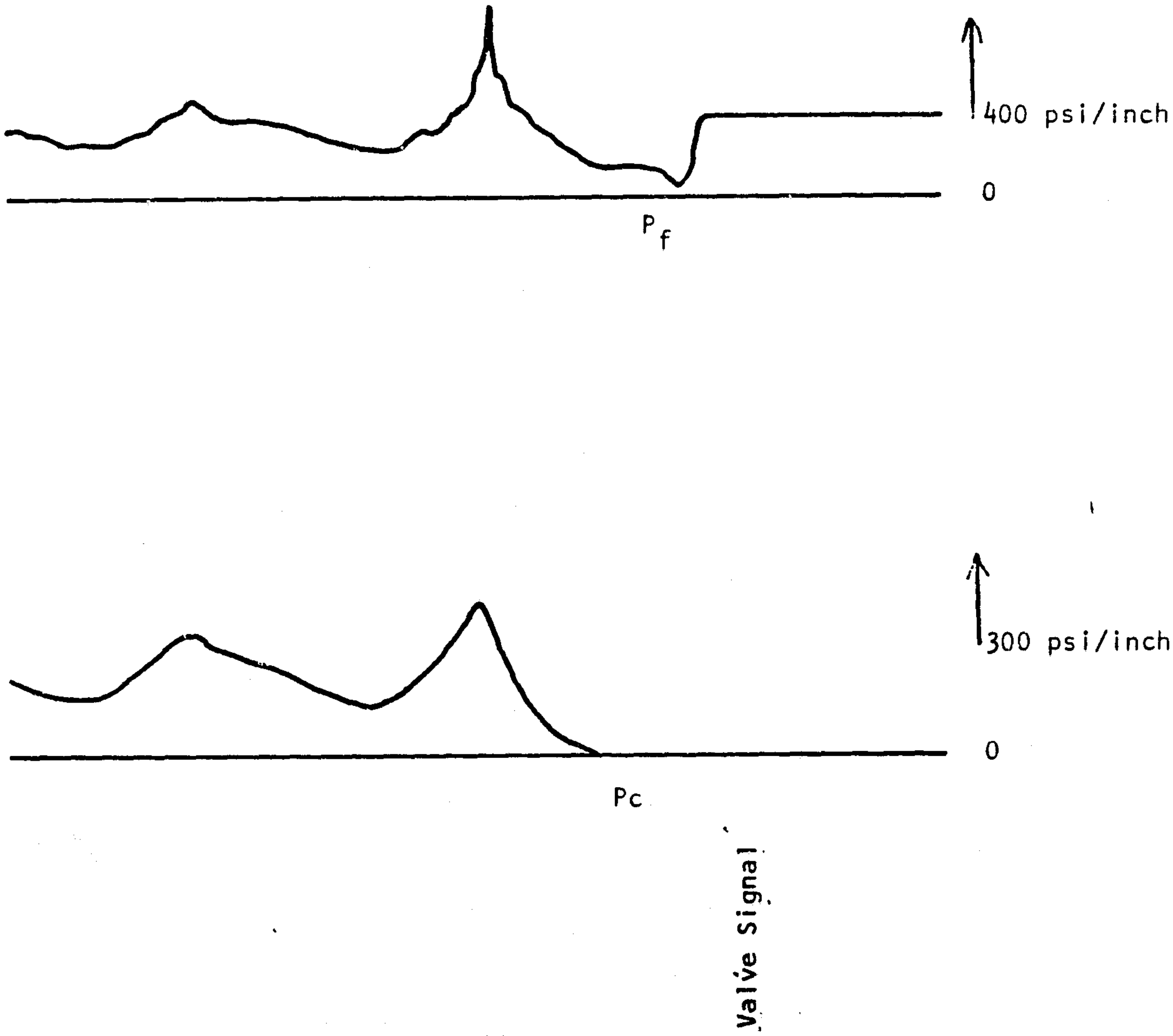


FIGURE 44

2.5 COMPARISON WITH MINOR MODIFICATION TESTING (continued)

2.5.1 Hot Restart (continued)

chamber pressure transients, detonations in the branch tubes produce a transient pressure increase in the fuel system which is less damped. The detonation in the branch tube itself constitutes a significant failure risk while pressure transients caused by surge flow into the catalyst bed do not.

2.5.2 Estimation of Gas Generator Life

The estimation of expected life capability of the ICGG was accomplished by comparing changes in steady state roughness versus firing time for the first few hours of life with those exhibited on Minor Modification Gas Generators. The small data base, coupled with the bed cylinder compression phenomena on Unit S/N D204, makes this evaluation somewhat subjective. Note that Minor Modification units exhibit a life limit (based on unacceptable overshooting during pulse mode operation) of approximately 20 to 25 hours. This commonly corresponds to a roughness of approximately 200 ps- peak-to-peak.

Comparison in the rate at which roughness increases in early life shows Minor Modification units increasing approximately 20 psi peak-to-peak in the first four hours of life. A decrease in roughness was noted on Unit S/N D204 between the first and second ATP's (from 27 psi to 24 psi peak-to-peak in 3.8 hours of firing). Unit S/N D204A saw a similar decrease between ATP-1 and ATP-2 (27 psi to 21 psi in the first 1.2 hours of firing). The injector verification hot fire Unit S/N D203A (which was almost identical to the final ICGG design) saw an increase in roughness from 27 to 39 psi in the approximately four hours of firing time.

2.5 COMPARISON WITH MINOR MODIFICATION TESTING (continued)

2.5.2 Estimation of Gas Generator Life (continued)

Assuming the ratio of the rate of roughness increase is no worse than that for the Minor Modification typical (20 psi/four hours) to the worst ICGG (S/N D203A, 12 psi/four hours), then if the life limit is reached at the same absolute roughness (approximately 200 psi peak-to-peak); the projected life of the ICGG should be at least:

$$\frac{20}{12} \quad X \quad 20 \quad = \quad 33.3 \text{ hours.}$$

The average Minor Modification unit runs somewhat over 20 hours and the injector verification unit did not have all of the refinements of the final design, (these included some foam processing deleted in the verification unit and tightening of injector branch tube dimensional tolerances on D204 and D205 to improve evenness of injector flow distribution). Based on the above assumptions and information, an estimated life of 35 hours minimum is projected for the ICGG.

2.5.3 Surface Temperature Limit (350°F)

The gas generator was not fired in an altitude facility for these tests. Verification of the ability of the design to maintain an exposed surface temperature at or below 350°F was done by analysis.

3.0 CONCLUSIONS

- Based on the results described above, the Increased Capability Gas Generator appears to have unlimited hot restart capability in the range of feed pressures from the 400 psi to 80 psi. It must be recognized that the effects of vacuum on hot restart were not addressed and that due to limitations in testing time, only beginning-of-life bed conditions were tested. No starts with bubbles were performed as this was outside the scope of the program.

- Based on roughness from early Mission Duty Cycles on S/N D204, S/N D203A and S/N D204A, a minimum expected life of $\geq$ 35 hours is projected for the Increased Capability Gas Generator.

- Based on thermal analysis, this design will maintain a surface temperature of $\leq$ 350°F.

4.0 RECOMMENDATIONS

This section is divided into two parts. The first part deals with the instrumentation and testing at the APU level of the two units delivered under this contract. The second part deals with an examination of areas for further design, analysis, and testing.

4.1 APU TESTING OF S/N D204A and S/N D205

The testing of D204A in the RRC sea-level cell has established that the units can safely hot-restart early in life with a variety of initial feed pressures and soakback conditions. While it is important to verify these results at the APU level, and testing at RRC indicates no concern over the number of hot restarts, the accumulation of a large number of hot restarts early in life is not representative of typical life requirements. A realistic assessment of hot restart requirements would indicate that it is still an emergency system. If a meaningful life test is to be conducted, it should probably include some hot restarts but not significantly more than are likely to be accumulated during the life of a gas generator bed. Under the assumption that a hot restart more often than every third mission is unlikely, and that a mission constitutes 81.1 minutes of firing, this would mean that 10 hot restarts in 40 hours of testing should be a reasonable test goal. In order to provide a baseline for gas generator life potential, it is recommended that a minimum of 10 hours be accumulated before any hot restarts are conducted.

It must be recognized that two areas of potential impact on hot restart were not addressed at RRC. The effect of vacuum on hot restart was not addressed as the extensive set-up required was outside the cost and schedule consideration of this program. The second area is

the effect of bubbles in the fuel system. The impact of bubbles is primarily an adiabatic compression heating/detonation problem. While testing such a condition was not within the scope of RRC testing, it is recognized that the potential for such a condition exists at JSC and on the vehicle. It is important that soakback temperatures be controlled to prevent formation of bubbles due to fuel decomposition. The formation of bubbles during soakback should be considered reason for restart abort until the system is purged. A bubble trap should be installed in the fuel line to prevent bubbles originating in the tank from reaching the gas generator. The elimination of active cooling from the gas generator, while a major step toward APU system improvement, needs to be accompanied by other system upgrades. These should be tested as a system and should include:

1. Use of a passively-cooled/standoff fuel pump.

2. Operation with N_2 pressurant only for the fuel system.

3. Passive reduction in valve soakback temperature by one or a combination of the following:

   a. Reduction of voltage to valve solenoids.

   b. Using the shutoff valve to control pulse mode operation, thus reducing energy to be dissipated.

   c. Shunting heat from the valve to an isolated heat sink (may be used with or without thermoelectric augmentation).

In order to adequately understand any data gained from such a test series, it is imperative that adequate instrumentation be installed

in the system. The listing of instrumentation in Tables XV, XVI, and XVII is divided into three areas: the gas generator, the valve, and the APU fuel system. All flow and pressure transients should be recorded on high speed oscillograph for maximum resolution.

4.2 AREAS FOR FURTHER DESIGN, ANALYSIS AND TESTING

In the course of fabricating and testing the deliverable items under this contract, RRC has endeavored to improve the design and hardware as much as possible. It must be recognized that while these units offer an excellent baseline for an Improved Gas Generator, there are a number of areas in which work needs to be done to fully optimize the gas generator.

Areas for future work should include, but not necessarily be limited to:

1. Design, analysis and test effort to lower the soakback temperature of the valve. This would have to address not only insulation, but also design of valve mounting structure, detailed examination of valve logic, torque motor voltage requirements and control and alternative methods of dumping heat from the valve.

2. Analysis, design and test to assure the ability of the Gas Generator Subsystem (including the valve) to handle any credible bubble which could be generated in and transported from the fuel tank. Tests performed at RRC, while less expensive and less complicated to perform, have to this date been performed exclusively with a pressurized tank-type feed system. In order to adequately simulate

TABLE XV

GAS GENERATOR INSTRUMENTATION REQUIREMENTS*

INSTRUMENT	TYPE	**LOCATION	RRC INSTALLED	JUSTIFICATION
T_7 and T_{7R}	Type "K" Thermocouple	Support Tube	Yes	Define Accurate Thermal Profile during Operation, Soakback, and Hot Restart. Provide Model Verification.
T_8 and T_{8R}	"	Injector Well	Yes	
T_5 and T_{5R}	"	Thermal Shunt	Yes	
T_4	"	Feed Stem	Yes	
T_3	"	Feed Stem	Yes	
T_2	"	Feed Stem	Yes	
T_P	"	Valve Mount Plate	Yes	

* ADDITIONAL TO FLIGHT TRASNDUCER AND TEMPERATURE SENSOR

** SEE FIGURE 25 for LOCATION INDEX.

TABLE XVI

GGVM INSTRUMENTATION REQUIREMENTS

INSTRUMENT	TYPE	LOCATION	REQUIREMENT
T_{VA} and T_{VB}	Type "K" T/C	Valve	Provide tracking of valve and fuel temperature during both soakback and operation.
T_{VS}	Type "K" T/C	Immersion in S.O. Outlet Port	
P_V	Strain Gage Pressure Transducer	Install in Pulse Control Outlet Port of Valve.	Provide tracking of crossover passage pressure transients during Hot Restart and pulsing. This will aid in defining extent of Gas Generator/Fuel System Dynamic Coupling.

TABLE XVII

APU FUEL SYSTEM INSTRUMENTATION REQUIREMENTS

INSTRUMENT	TYPE	LOCATION	REQUIREMENT
T_{FF}	Type "K" T/C	Immersion Fuel Feed from Pump	Provide data needed for thermal balance around the valve. Determine heating of fuel in valve, and fuel temperature in lines during soakback.
T_{FB}	Type "K" T/C	Immersion in Bypass Return to Pump	
P_{VI}	Strain Gage Pressure Transducer	Fuel Inlet Pressure to Valve.	Aid in defining fuel system dynamic behavior during Hot Restart and in the event of Bubble Flow through the system.
P_{VB}	Strain Gage Pressure Transducer	Fuel Bypass Pressure from Valve.	
$\dot{w}_{FI}$	Ramapo Flowmeter (0 to $\|2.5\|$ gpm, plus direction)	Fuel Feed Line.	Provide data need to complete Fuel System material balance, including identification of bubble size and location.
$\dot{w}_{FB}$	Ramapo Flowmeter (0 to $\|2.5\|$ gpm, plus direction).	Fuel Bypass Line.	
$\dot{w}_{PI}$	Ramapo Flowmeter (0 to $\|2.5\|$ gpm, plus direction).	Fuel Pump Inlet.	

4.2 AREAS FOR FURTHER DESIGN, ANALYSIS AND TESTING (continued)

feed system dynamics, RRC would prefer to use an APU-type positive displacement fuel pump. By operation, using a variable speed electric drive, RRC could perform accelerated system tests, with realistic fuel system dynamics at a cost much less than running APU-level tests.

3. Packing studies are needed to optimize bed life for this injector design. This is important as bed life is a strong function of the homogeneity of the initial catalyst pack and the amount of catalyst attrition caused by packing. In conjunction with this it is important to examine and optimize the bed plate configuration. This should not only address the problems which resulted in the compression of the S/N D204 bed cylinders but also address extension of gas generator bed life.